Nucleon-antinucleon annihilation at LEAR

…and what we (do not) understand about $N\bar{N}$ annihilation

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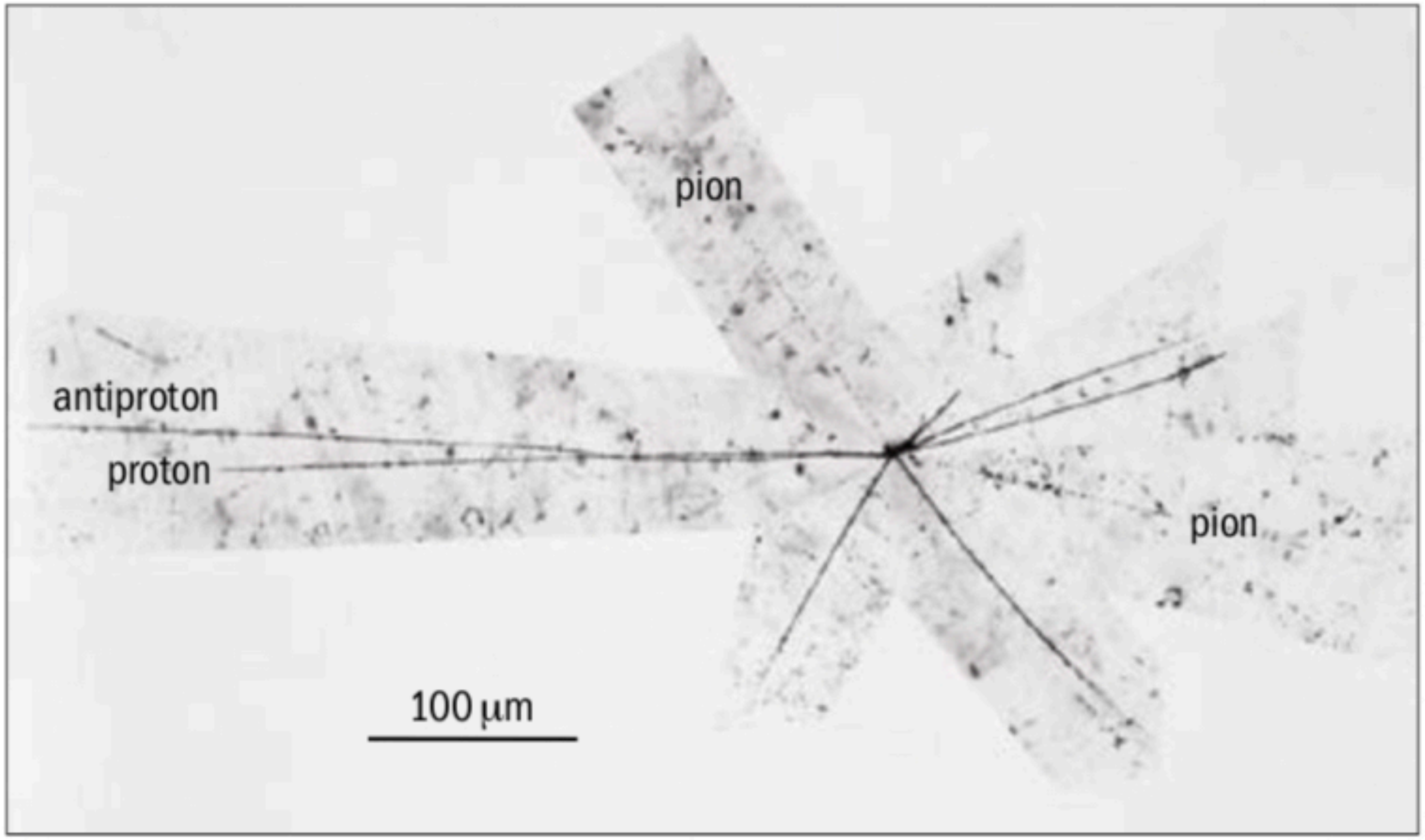
One of the first annihilations observed in emulsions



1956, Bevatron, Berkeley

O Chamberlain et al. *1956* Nuov. Cim. *3 447*

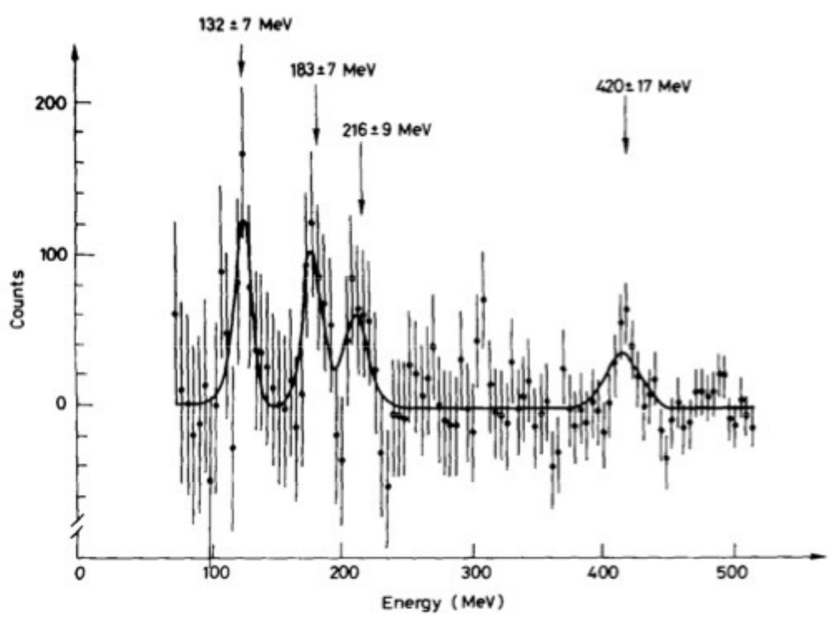
1970's: Evidence for $N\bar{N}$ bound states and resonances

Ca87

bibliography

Bound states

$\bar{p}$ (stop) p -> γ X



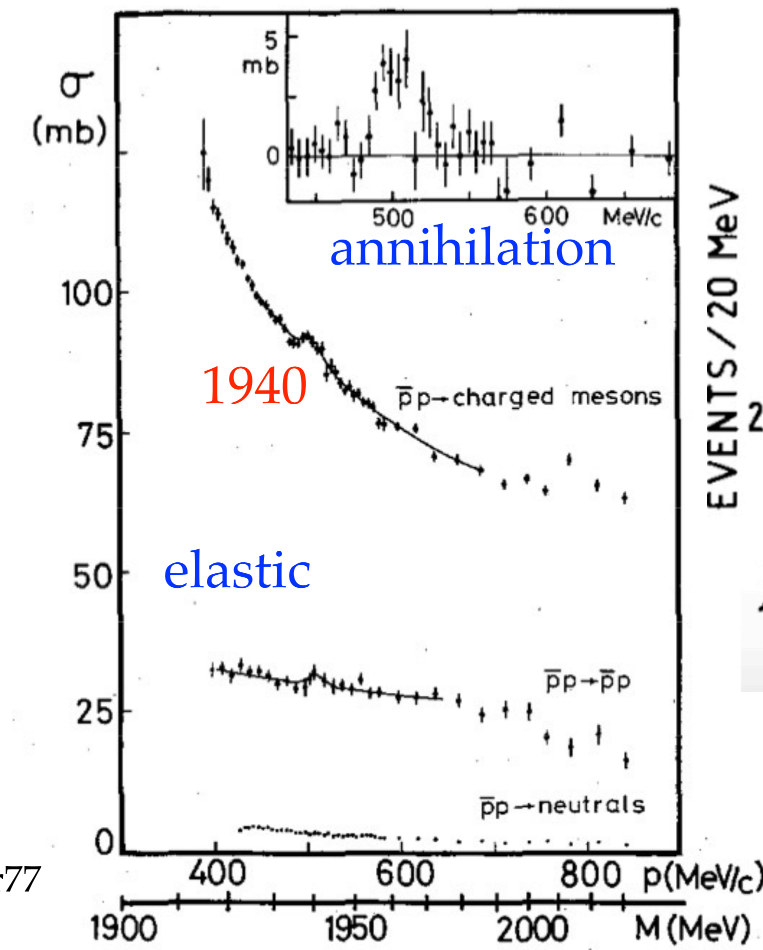
CERN-PS

Pa78

Resonances $M > 2m_p$

$\bar{p}p$ cross section

CERN-PS

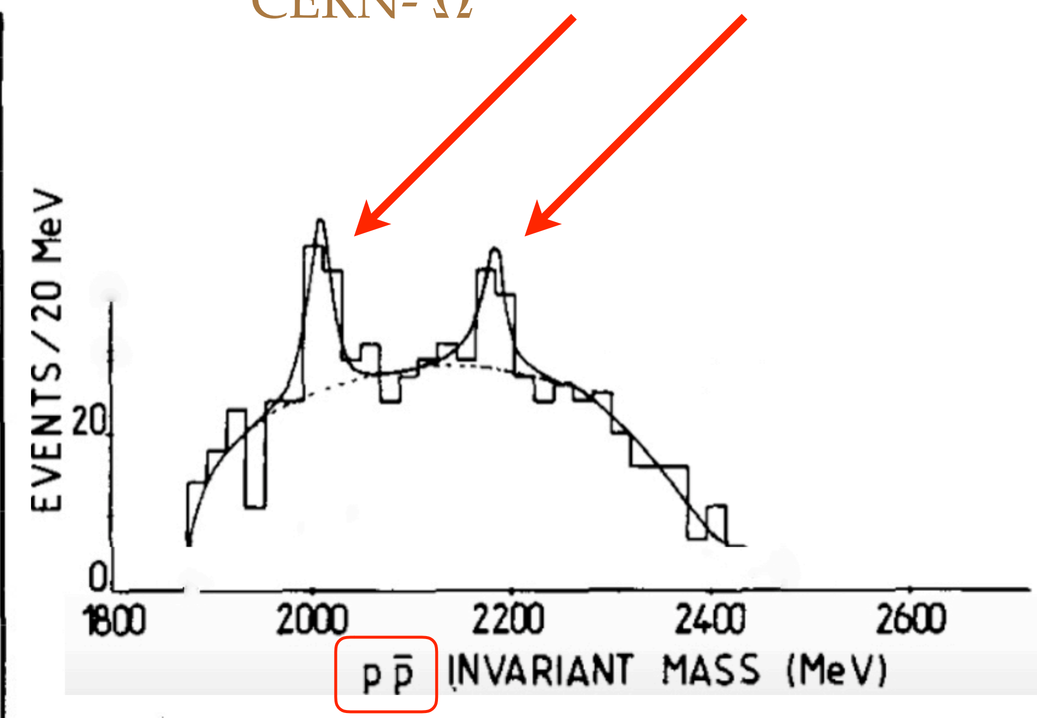


Br77

$\pi^- p$ -> p ($p\bar{p}$) π^-

9 GeV/c pions

CERN- Ω



Be77

…and seen by many others at Brookhaven, KEK…

Bound states and resonances (baryonium) were predicted in the $N\bar{N}$ system due to the attractive short range force.

$N\bar{N}$ potential =
NN potential x G-parity of exchanged meson

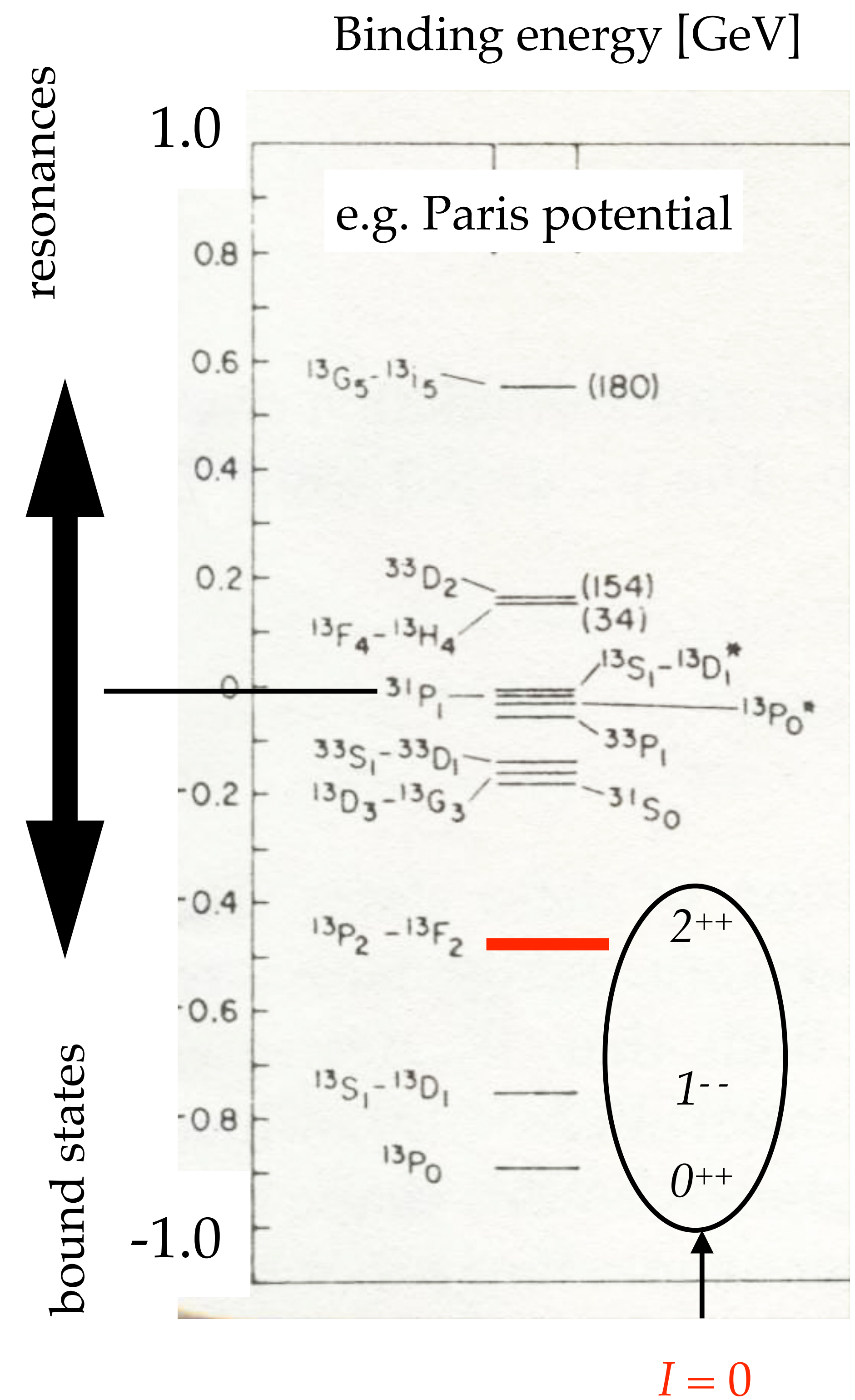
Short distance NN: repulsive ω exchange

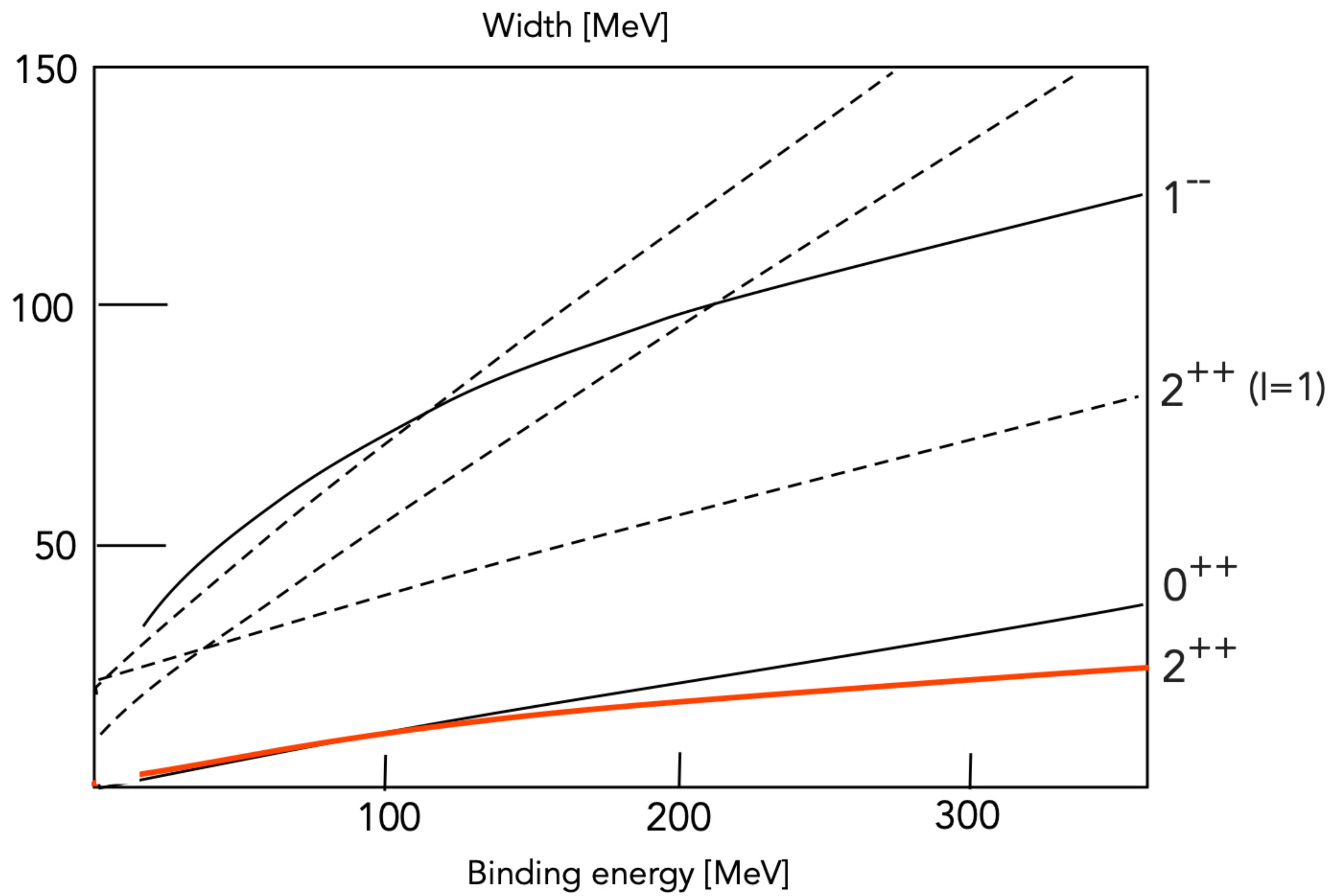
$G(\omega) = -1$: central force is attractive for ω

for both $\bar{p}p$ isospin $I = 0$ and 1

ρ contributes repulsion in isospin 1

Deeply bound: isospin 0 (charge neutral states)



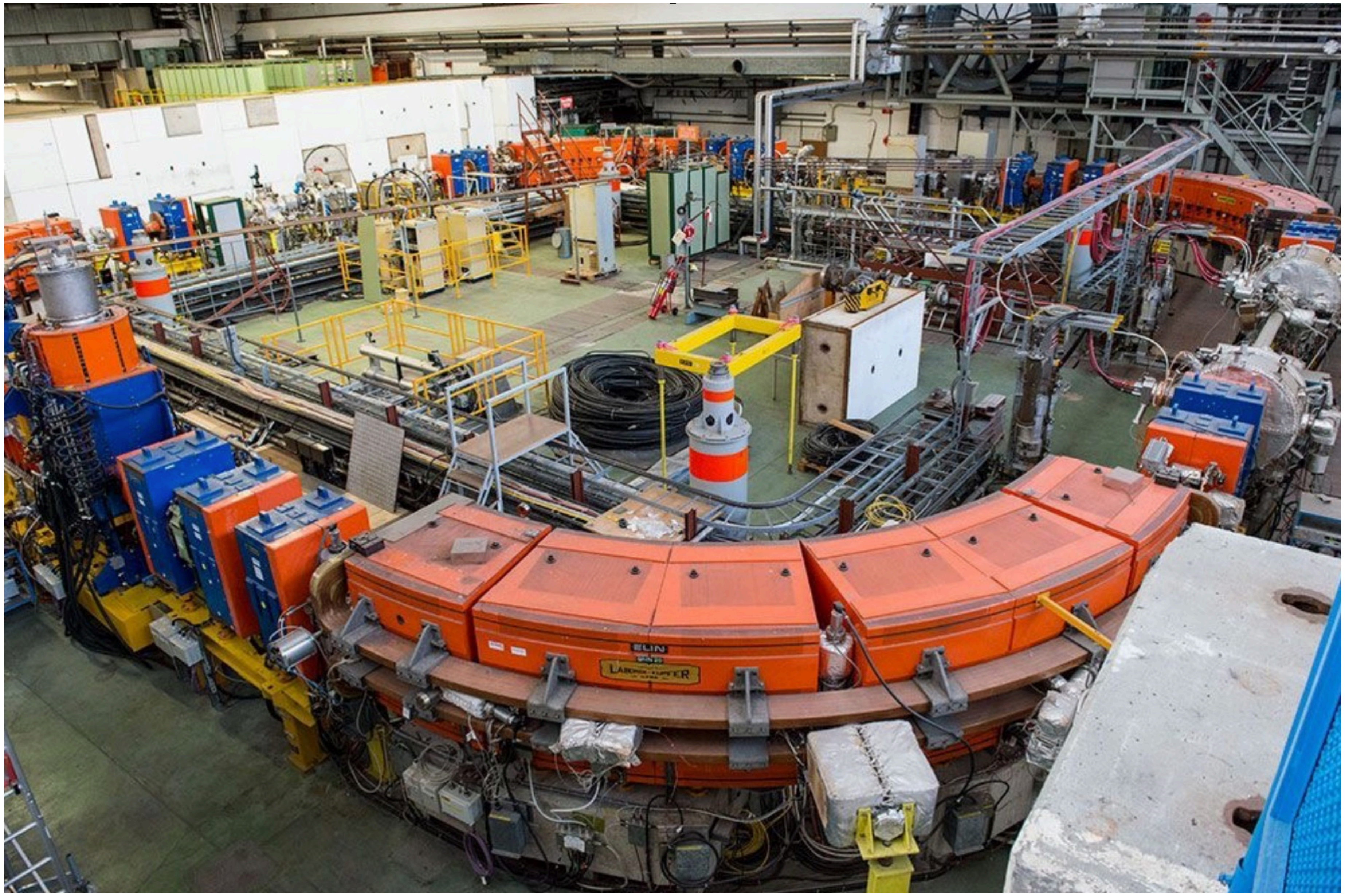


Short lifetime due to the annihilation process (range uncertain ~1 fm?): larger widths

Narrow $I = 0$ states: 2^{++}, 0^{++}

Main motivation for building a high intensity low energy, narrow momentum bite, and pure antiproton beam (LEAR)

Low Energy Antiproton Ring in the CERN South Hall (LEAR, 1983-1996)



3.5 GeV/c $\bar{p}$ into PS, 600 MeV/c from PS into LEAR -> [60 (2 MeV) — 1940] MeV/c, stochastic cooling, extraction (1 hour spill) to simultaneously > 1 experiment, $\Delta p/p < 10^{-3}$, 10^6/s

(1 $\bar{p}$ /15 min in 1955 at Berkeley!)

…but the states were not found at LEAR, baryonium remained elusive

Total of 35 LEAR Experiments, 15(?) on annihilation: ★ 350 publications

PS170 Precision Measurements of the Proton Electromagnetic Form Factors in the Time-like Region and Vector Meson Spectroscopy

PS171 Study of Proton-Antiproton Interactions at Rest in a H_2 Gas Target at LEAR (ASTERIX) ★

PS173 Measurement of Antiproton-Proton Cross-Sections at Low Antiproton Momenta

PS177 Study of the Fission Decay of Heavy Hypernuclei

PS179 Study of the Interaction of Low-Energy Antiprotons with H_2,He_3,He_4,Ne-Nuclei Using a Streamer Chamber in Magnetic Field

PS182 Investigations on Baryonium and Other Rare pp Annihilation Modes Using High-Resolution π^0 Spectrometers

PS183 Search for Bound $N\bar{N}$ States Using a Precision Gamma and Charged Pion Spectrometer at LEAR

PS184 Study of Antiproton-Nucleus Interaction with a High Resolution SPESII Magnetic Spectrometer

PS186 Nuclear Excitations by Antiprotons and Antiprotonic Atoms

PS187 A high statistics study of antiproton interactions with nuclei

PS197 The Crystal Barrel: Meson Spectroscopy at LEAR with a 4π Detector ★

PS201 Study of antiproton and antineutron annihilations at LEAR with OBELIX, a large acceptance and high resolution detector based on the Open Axial Field Spectrometer ★

PS202 JETSET: Physics at LEAR with an Internal Gas Jet Target and an Advanced General Purpose Detector

PS203 Antiproton Induced Fission and Fragmentation

PS208 Decay of Hot Nuclei at Low Spins Production by Antiproton-Annihilation in Heavy Nuclei

Global features of proton-antiproton annihilation at rest

Charged particles : from bubble chamber data at rest (~1970, CERN & Brookhaven) Ar69

Gh74

Prong (charged)	%
0	4.1 (+0.2-0.6)
2	43.2 (+0.9-0.7)
4	48.6 (+0.9-0.7)
6	4.1 (+0.2-0.2)

contain ~7% η , ~6 % K

and ~60% of all annihilations have > 1 π^0

unknown before Crystal Barrel at LEAR

Fireball, pions evaporate from hot gas? Ki81

More complicated:

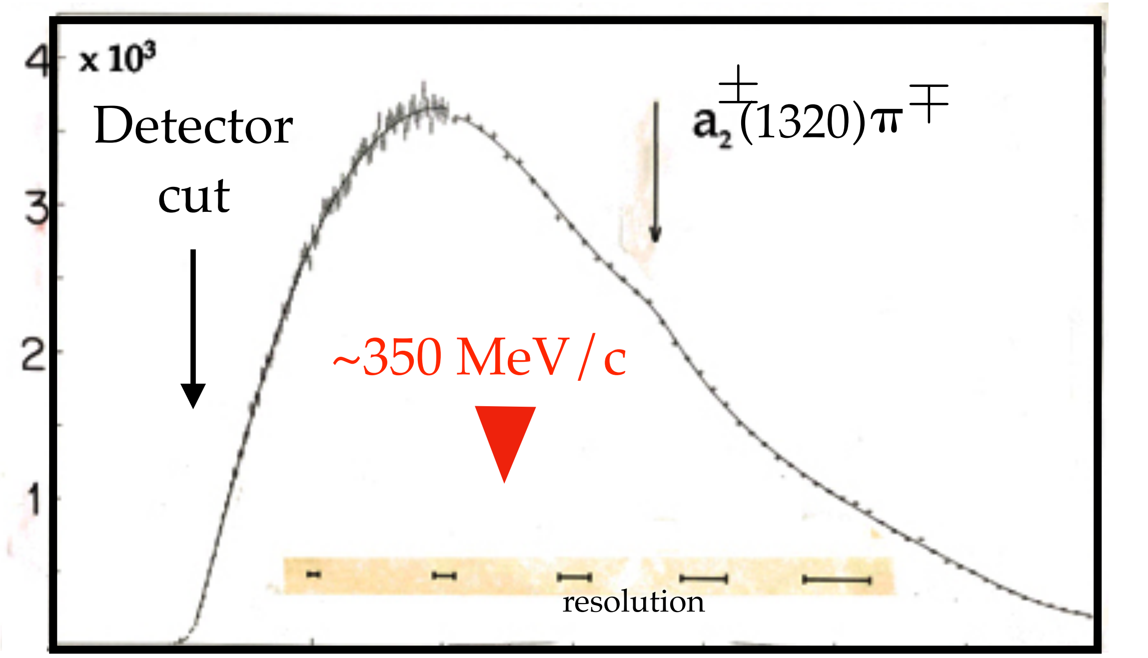
- mostly via intermediate resonances:

e.g. $2\pi^+2\pi^-\pi^0$: $\omega\rho^0, \omega f_2(1270)$, ...

- QN conservation rules from $\bar{p}p$ at rest (S, P atomic states)

Inclusive charged pion spectrum $\bar{p}p$ at rest

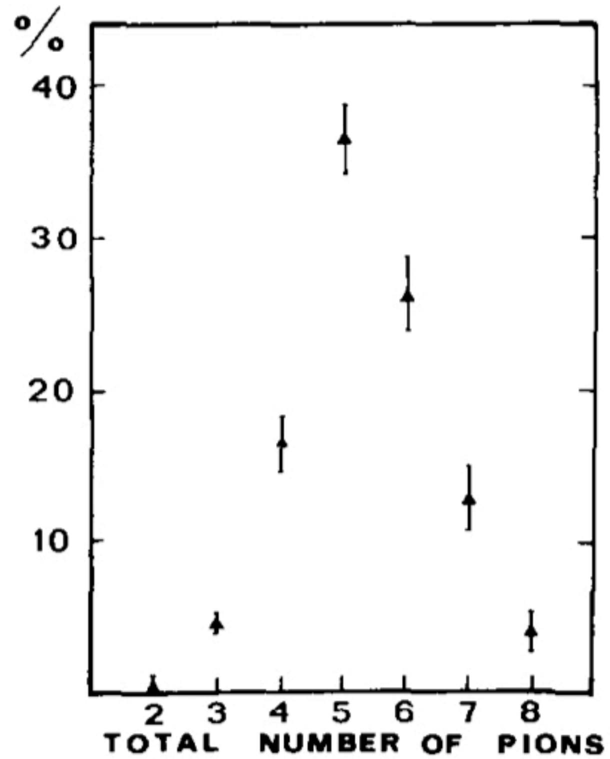
(ASTERIX)



Ah85

Pion multiplicity

Charged + neutral
pion multiplicity



1.6 GeV/c in Gargamelle (CERN) bubble chamber with heavy liquid (propane-freon) and converting the photons (e^+e^-) from neutral pions

$$< n(\pi^0) >= 1.92 \pm 0.04$$

$$< n(\pi^\pm) >= 3.46 \pm 0.04$$

Statistical distribution

Fe77

Va88

$\overline{\text{p}}$ at rest: distribution not available before LEAR (due to low antiproton fluxes at low energy). In particular no data on multineutral pion multiplicities

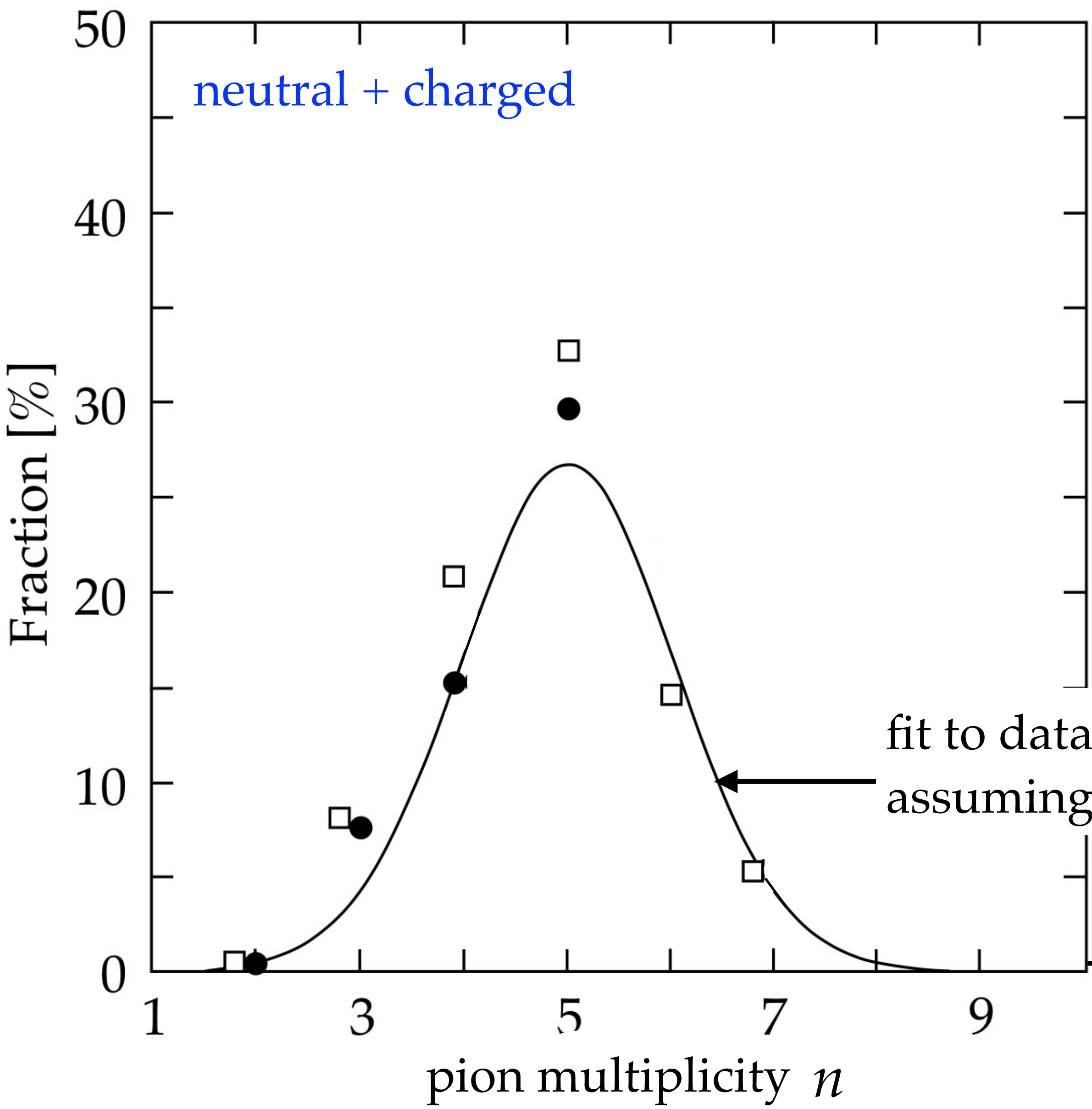
Distribution between neutral and charged for a given number of pions *n*

Factorial law:

$$\frac{1}{n_+!n_-!n_0!}, \quad n = n_+ + n_- + n_0$$

Pa60,63

Current status at rest: liquid H_2



● data (BBC + Crystal Barrel)

□ factorial law using data

e.g. $6\pi^\pm$ is known but not $6\pi^0$

	□	●
2π	0.50 (0.01)	0.33 (0.01)
3π	8.1 (0.5)	7.5 (0.4)
4π	20.9 (1.8)	16.5 (0.6)
5π	33.3 (1.2)	30.0 (0.9)
6π	14.7 (1.4)	%
7π	7.0 (0.7)	

$< n(\pi^0) >= 2.0 \pm 0.2$

$< n(\pi^\pm) >= 3.0 \pm 0.2$

$\sigma = 1.04 \pm 0.01$

total = 84.5 %, add $K, \eta, \omega \to \pi^0\gamma$...

Fair to good agreement

ASTERIX

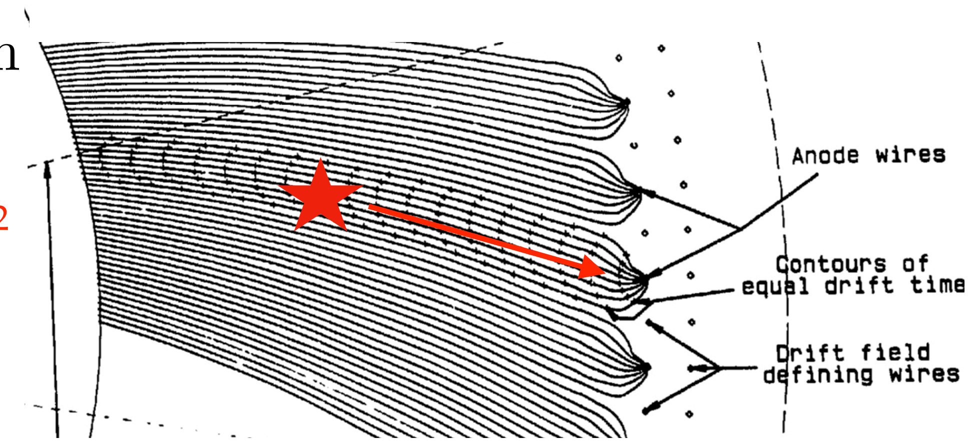
Solenoid 8kG (DM1 from LAL-Orsay)

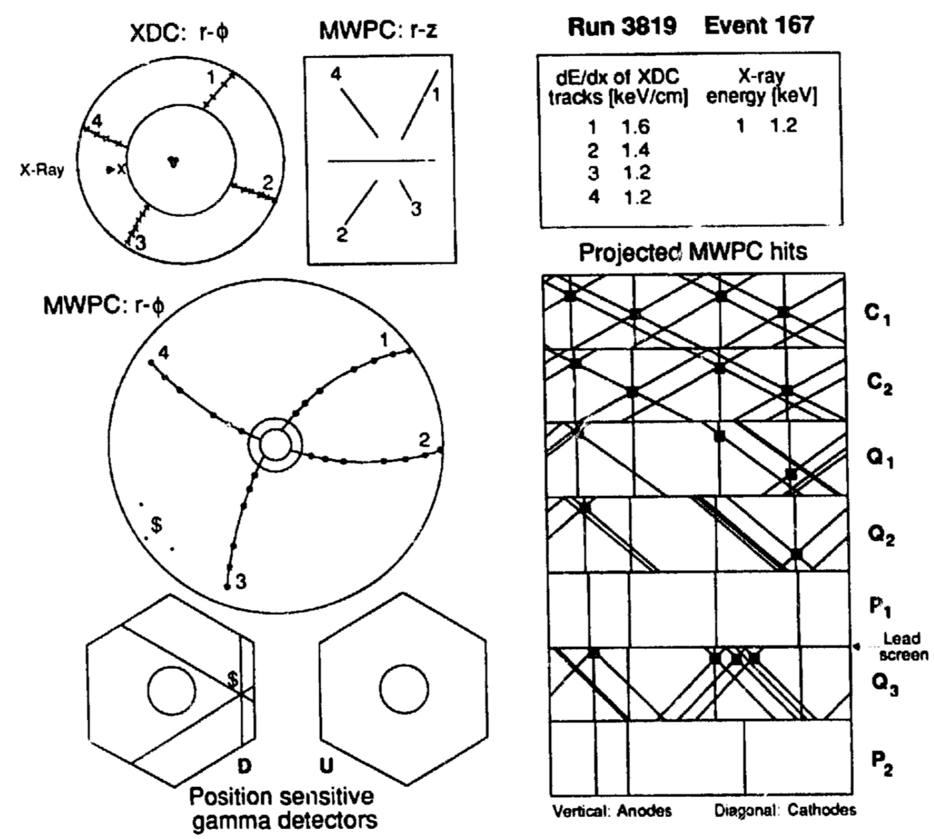
argon/ethane X-ray drift chamber (>1 keV)

105 MeV/c $\bar{p}$, H_2 gas at NTP

6 μm

H_2





4 prong event

7 MWPC

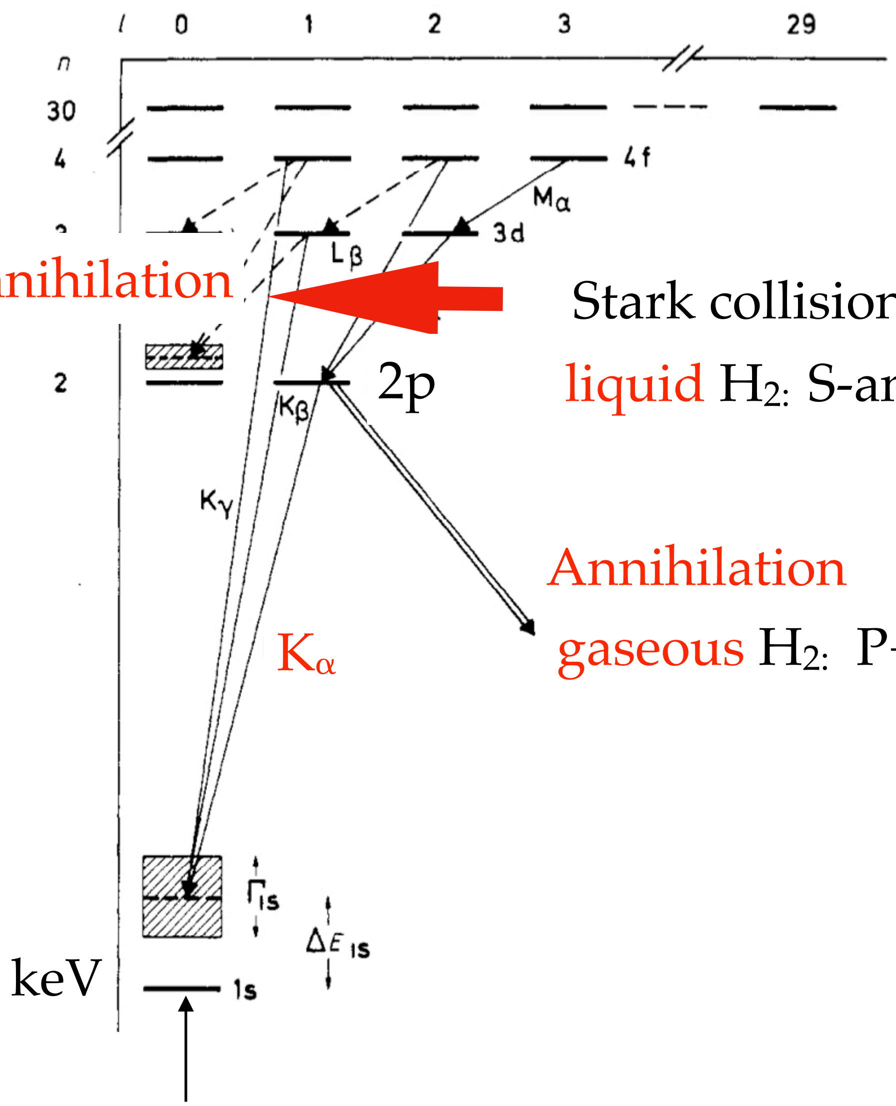
cathode strips

limited γ capability with Pb converter

Ah90

Stopping $\overline{p}$ in H_2 leads to $\overline{p}p$ atoms

(e.g. next talk)



capture: n = 30

Annihilation

Stark collision effect in
liquid H_2: S-annihilation

2p

Annihilation
gaseous H_2: P+S-annihilation

K_α

9.37 keV

Repulsive

LEAR:

Ba89

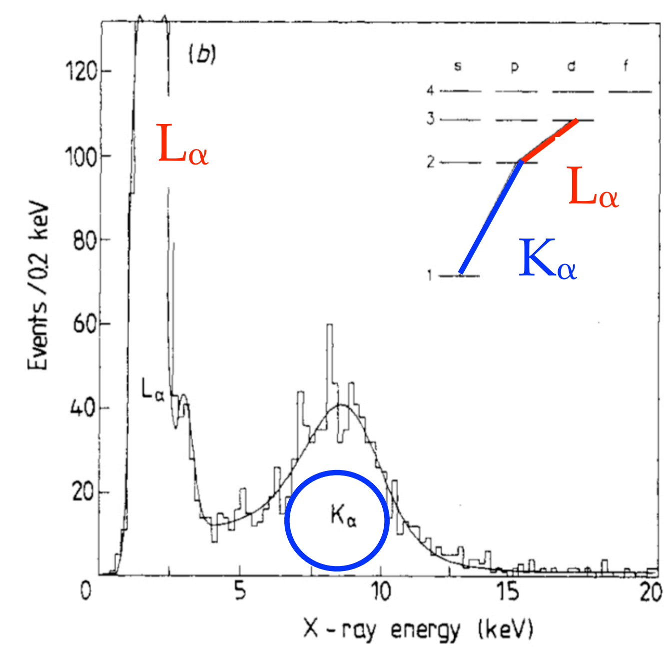
1s level shift: -0.72 ± 0.04 keV
Width: 1.11 ± 0.07 keV

First observation of K_α Ah85b

ASTERIX in gas at NTP

Reduce bremsstrahlung from prongs:

0 prong + L-coincidence

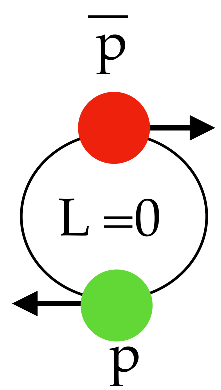


Zi88

Vary target density: new annihilation spectroscopy

Mostly annihilation from S-states:

In liquid:

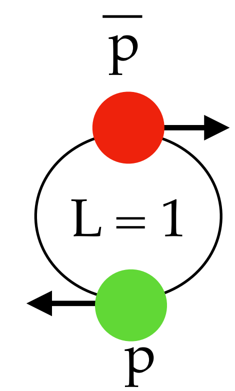


BBC, Crystal Barrel

Annihilation from P-state (2p):

gas NTP: ~13% L/ann.

Trigger on L-series:



NEW by ASTERIX!

In gas @ NTP (no trigger): ~50/50 S/P →

Fraction of P-wave in liquid and gas at rest:

$\bar{p}p \to \pi^+\pi^-, K^+K^-, K^0\bar{K}^0$ $\quad J^{PC} = 0^{++}, 1^{--}, 2^{++}\ldots \quad n^3P_0, n^3S_1, n^3P_2$

$\bar{p}p \to \pi^0\pi^0$ $\quad J^{PC} = 0^{++}, 2^{++}\ldots \quad n^3P_0, n^3P_2$ suppressed in liquid H_2

- P wave in liquid: $$f_p = \frac{B(\pi^0\pi^0)_{liq}}{B(\pi^+\pi^-)_{2p}/2}$$ Am92

$\pi^0\pi^0$ is hard to measure in liquid because of much stronger $\pi^0\pi^0\pi^0$

→ 4π photon high resolution detector (Crystal Barrel)
and well defined stopping distribution (< 1 mm, 200 MeV/c @LEAR)

Needs cascade calculation with potential models (hadronic widths)
because $n \geq 2$ contributes to $\pi^0\pi^0$ $\quad f_p = (13 \pm 4)\%$ Ba96

- P-wave in gas (NTP): $K^0\bar{K}^0$: K_SK_L C=-1 hence S-wave only

$B(K^0\bar{K}^0)_S$ = B(liq)/87% = (8.7 ± 0.6) x 10^{-4} and f_S in gas (K_SK_L, ASTERIX)

↑ S-fraction

→ $f_P = 1 - f_S$ = (56 ± 7) % NTP

Do88

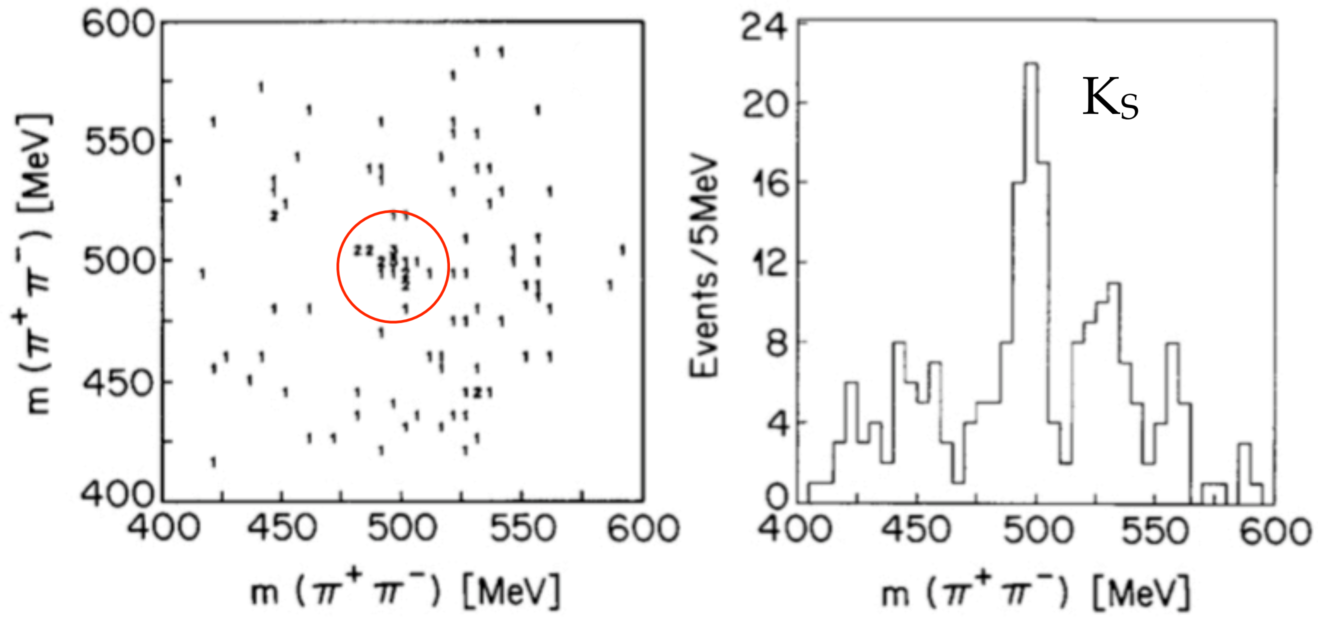
: K_SK_S C=+1 hence P-wave only

$K^0\bar{K}^0$ (8.7 ± 0.6) x 10^{-4} S

ASTERIX: 4 prong, L-coincidence, $K_S K_S$

$K^0\bar{K}^0$ (7.4 ± 2.8) x 10^{-5} P

~10 x suppression from P-wave!

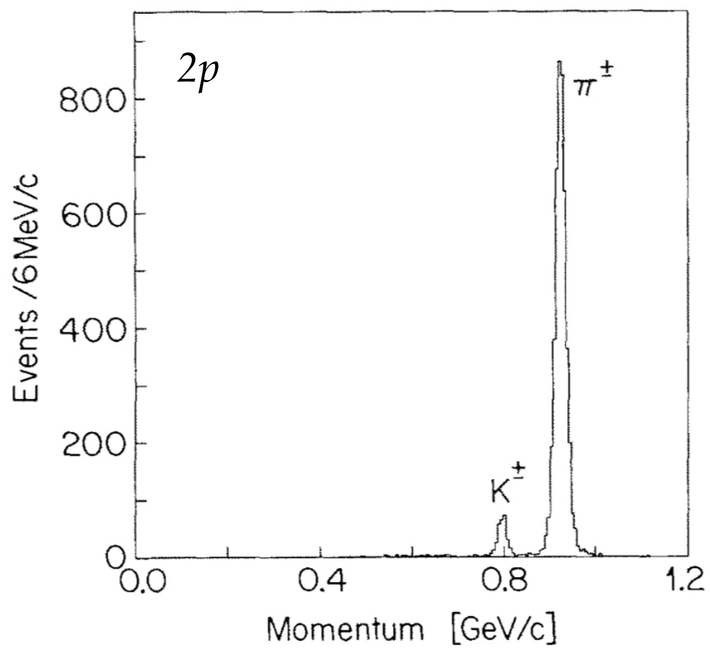


Do88

K^+K^- ~5 x suppressed from P-wave!

(2.87 ± 0.51) x 10^{-4}

P-wave (ASTERIX)

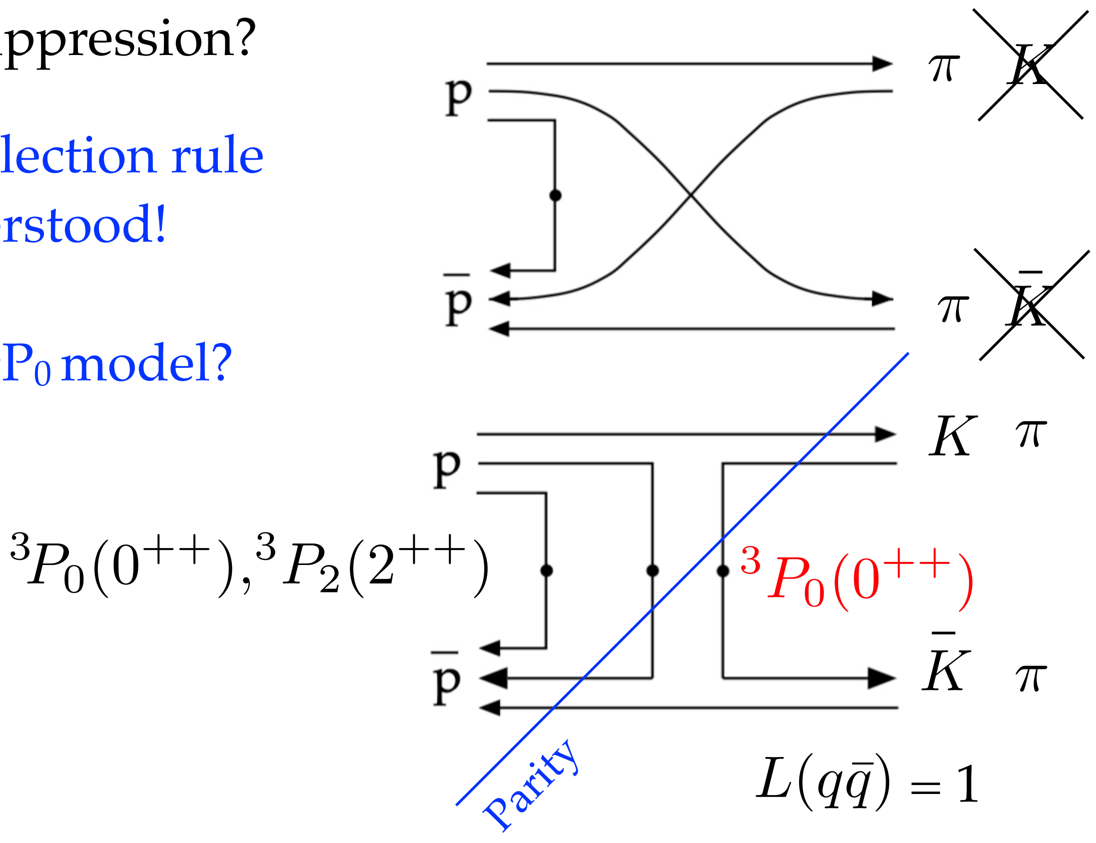


Do88b

Origin of suppression?

Dynamic selection rule not understood!

Quarks in $^3P_0$ model?



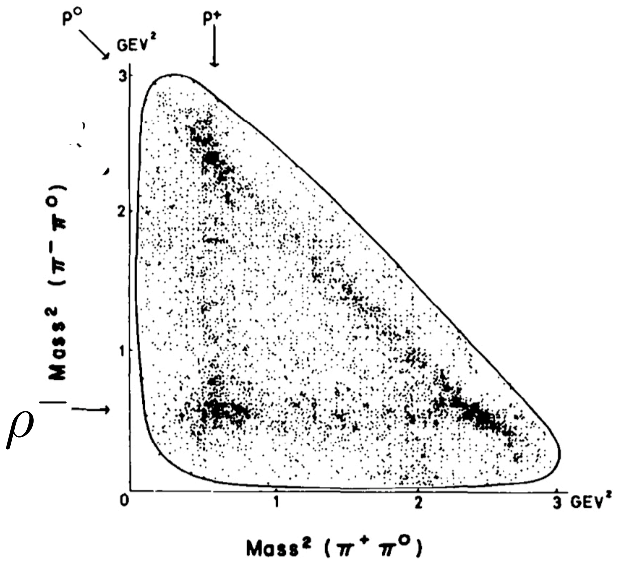
Kl05, AMy

Benefit from P-wave annihilation: at last a baryonium state?

Liquid (BBC)

$\pi^+\pi^-\pi^0$

Dalitz plot



ρ

$\rho\pi$ mostly $^3S_1$ (from angular distribution)

$^1S_0$ suppressed

$\rho\pi$ puzzle is also not understood

Fo68

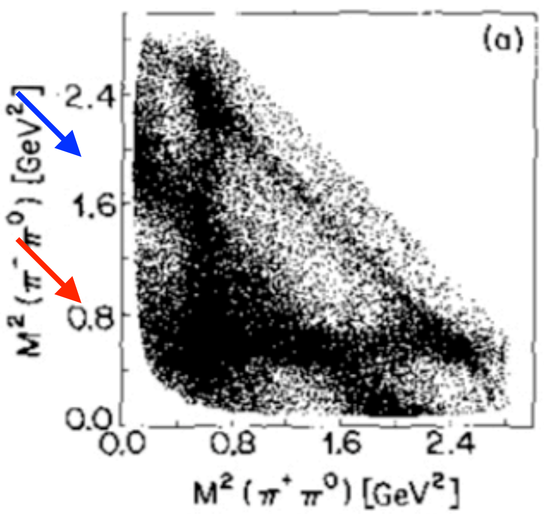
AMy

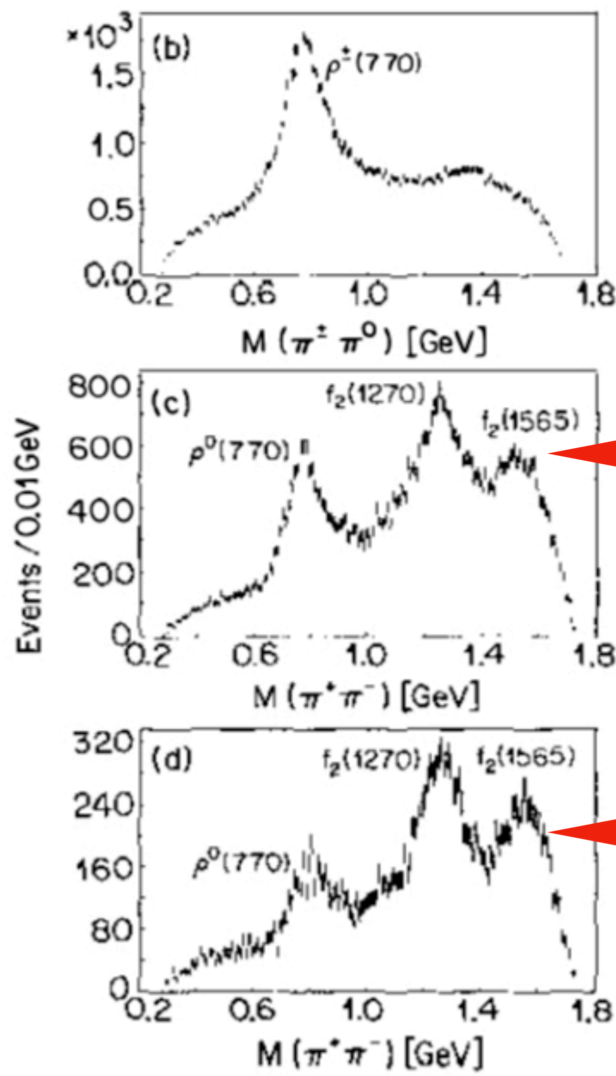
H₂ gas

ASTERIX

$f_2(1270)$

$f_2(1565)$





$\pi^\pm\pi^0$

no charged mode: $I = 0$

2^{++}, I=0, m=1565, Γ=134 MeV

$\pi^+\pi^-$

$2p$ strong signal

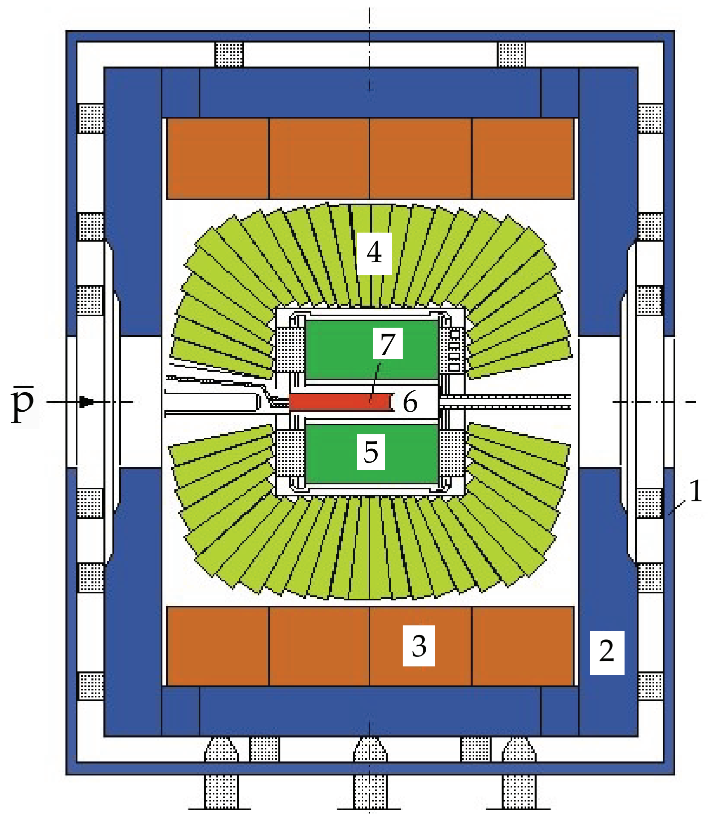
$\pi^+\pi^-$

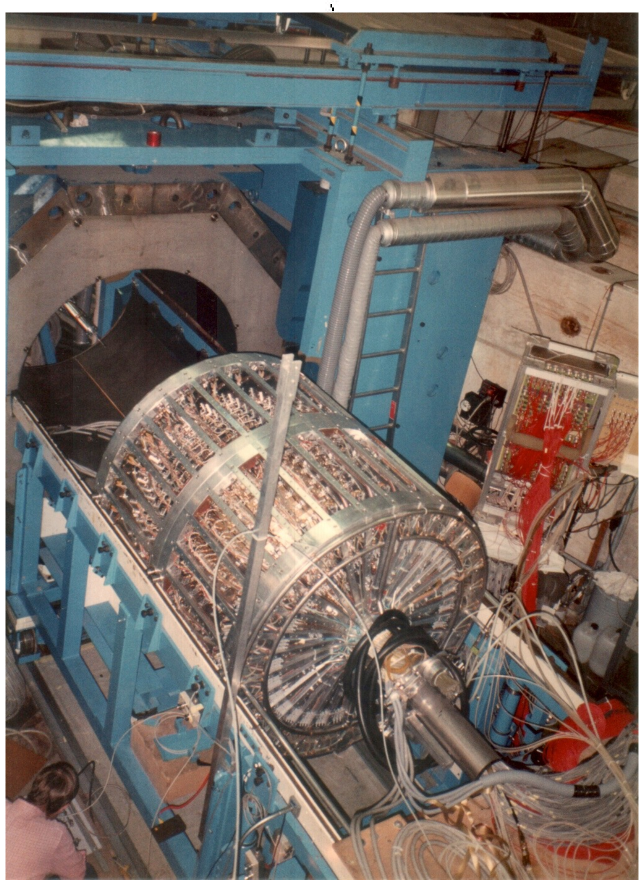
Ma90

supernumerary tensor meson $\bar{p}p \to 2^{++}$ (baryonium) π^0 ?

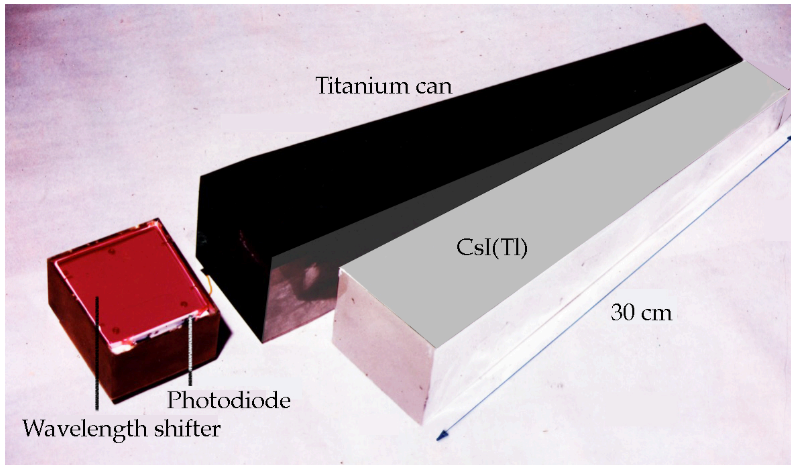
Crystal Barrel

Annihilation at rest in liquid, but with multiple photon detection ($\leq 10\gamma$)





- 15 kGauss
- 1380 CsI (Tl) crystals (97% x 4π)



- Jet drift chamber for charged products

CO_2/isobutane

- Emphasis on meson spectroscopy: new mesons discovered:

  $f_0(1370), \pi_1(1400), \eta(1410), a_0(1450), f_0(1500), \eta_2(1645)$

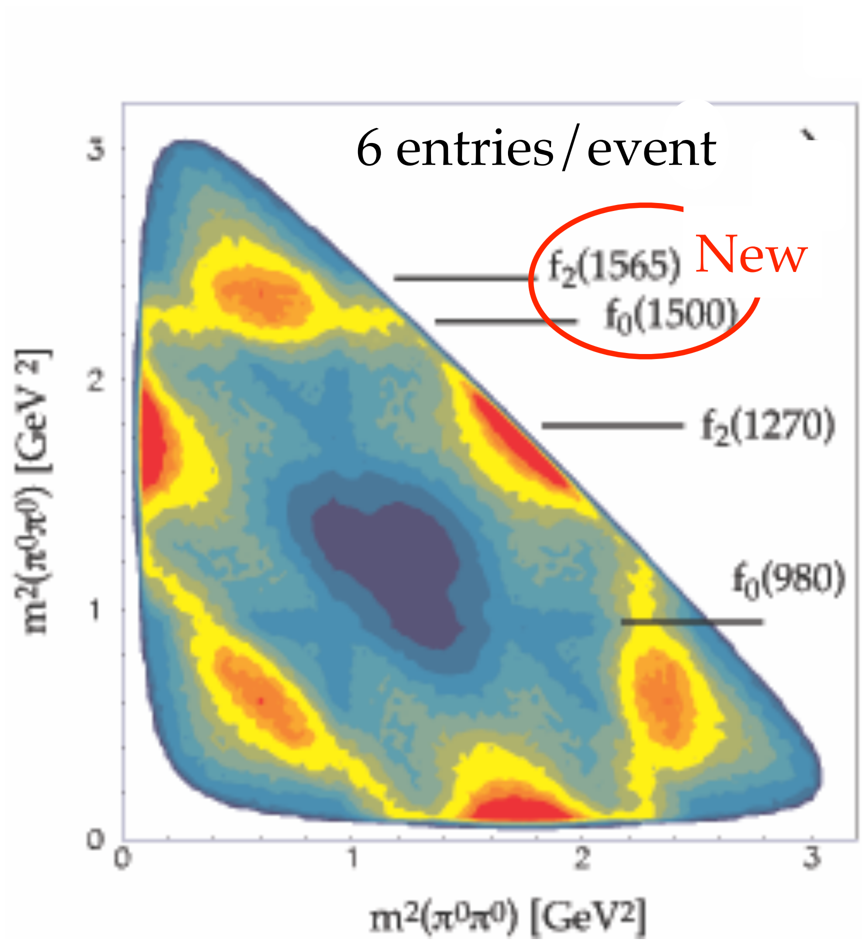
  with large data samples -> T-matrix analyses

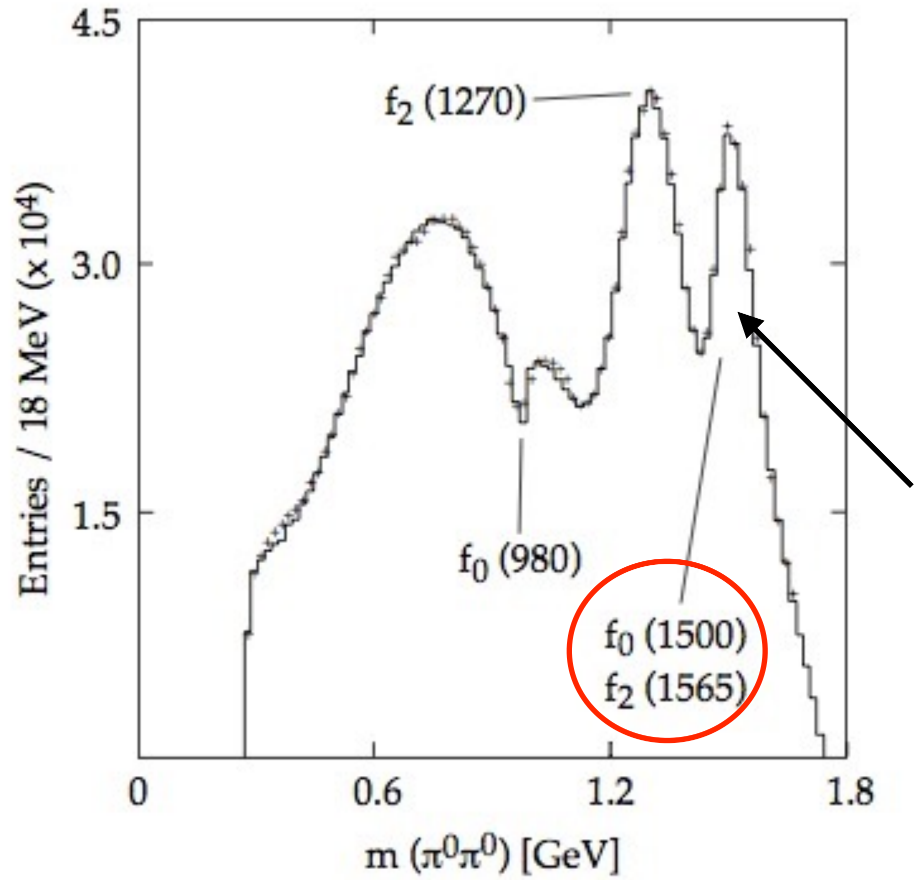
- Annihilation into 2 and 3 mesons

- Radiative annihilation

RMP98

Scalar and tensor mesons in 6γ events





$\bar{p}p \rightarrow \pi^0\pi^0\pi^0$ at rest

$f_0(1500)$ is a serious glueball candidate

100'000 events!

Terra incognita before LEAR: 60% of all annihilations have more than 1 π^0

- no background from $\rho^0 \not\rightarrow \pi^0\pi^0$
- C-parity conservation and neutral (non strange) mesons have a well defined C-parity

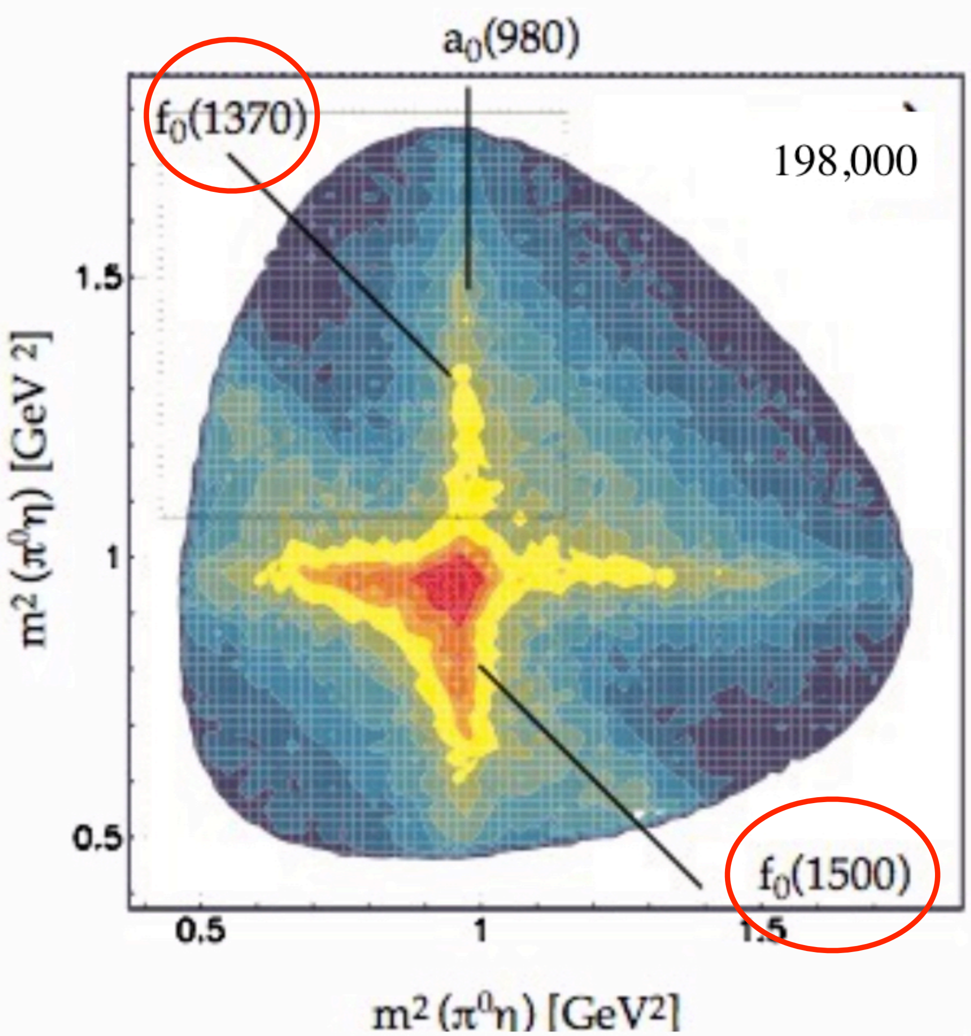
  e.g. $C(\pi^0) = +1$ while $C(\pi^{\pm})$ is not defined

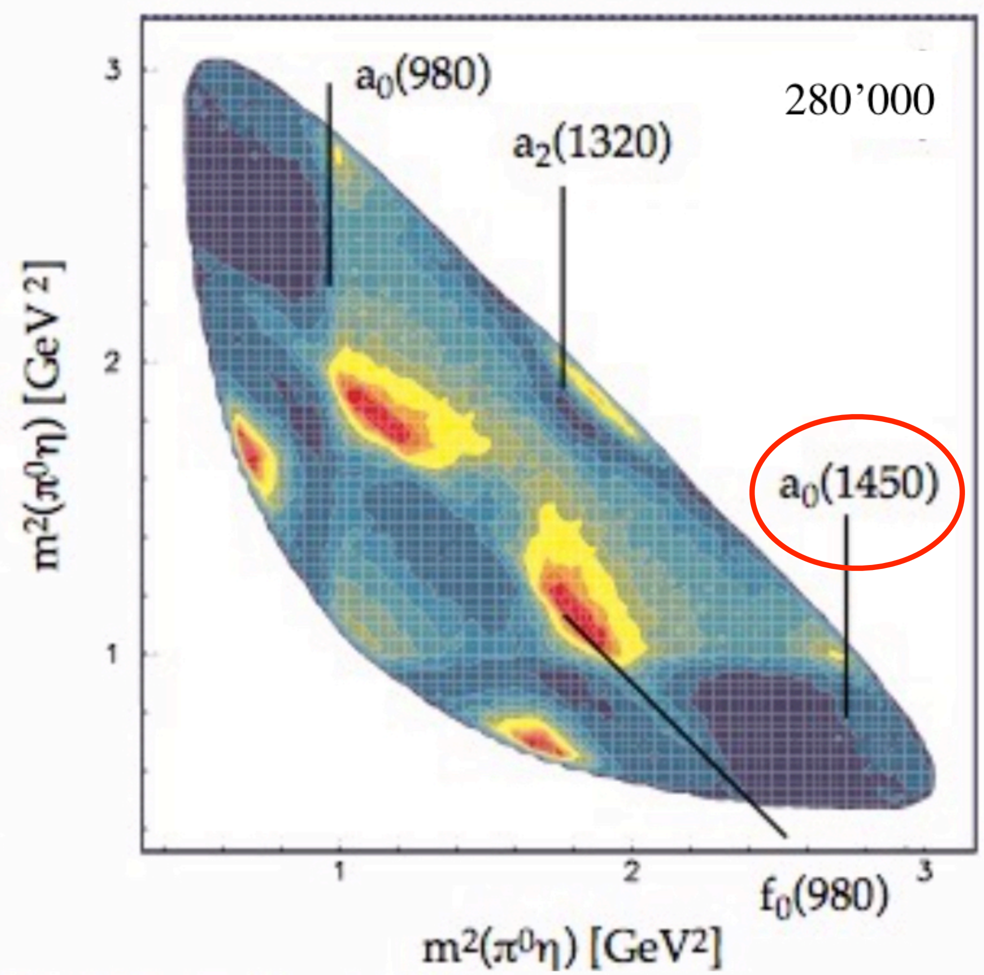
➡ Fewer partial waves, simpler analysis

Am96

more 6γ events…

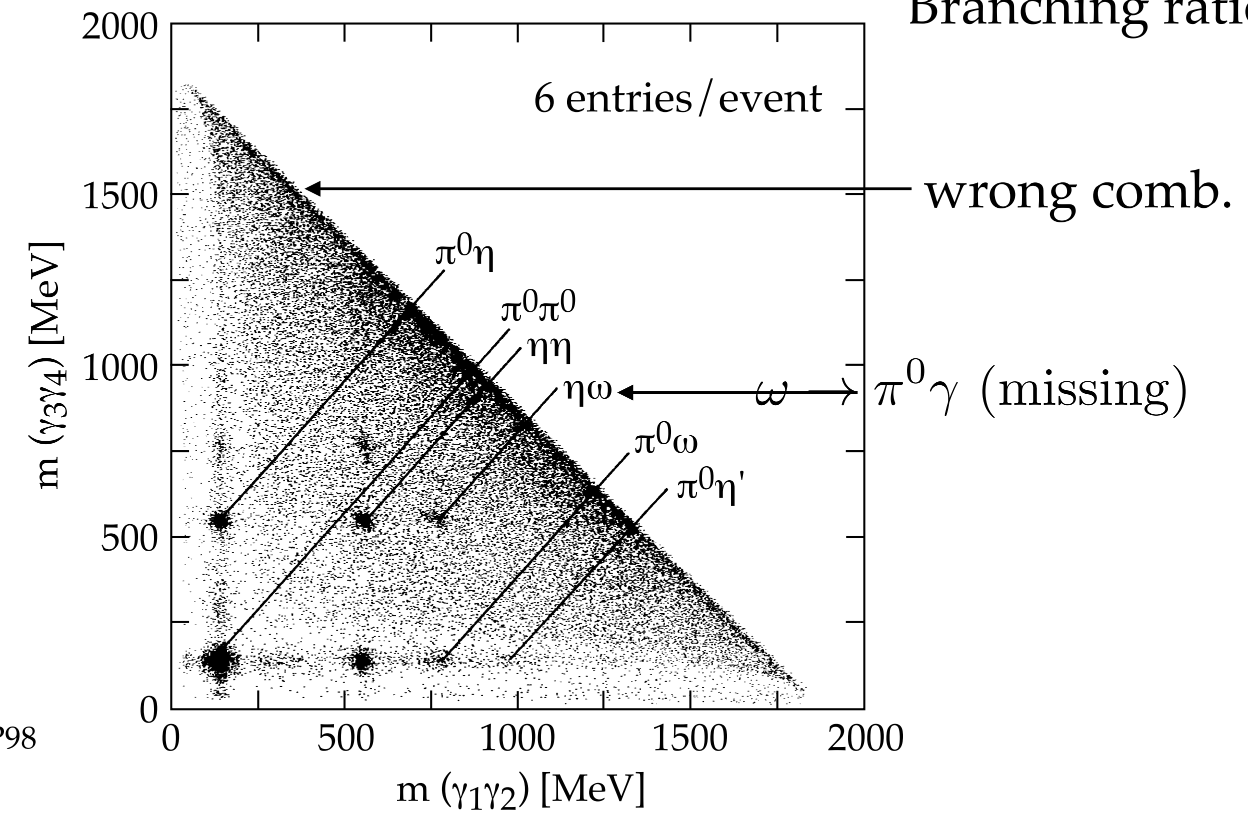
$\pi^0\eta\eta$





$\pi^0\pi^0\eta$

Annihilation at rest into two neutral mesons (4γ , Crystal Barrel)



RMP98

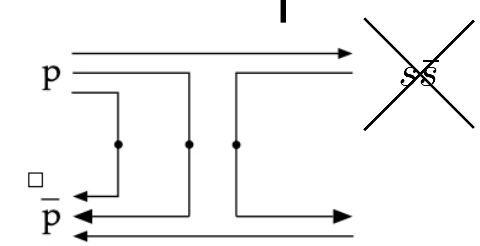
Branching ratios: 10^{-3} - 10^{-4}

$$\eta = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin(\theta_i - \theta_P) - s\bar{s}\cos(\theta_i - \theta_P)$$

$$\eta' = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos(\underbrace{\theta_i - \theta_P}_{\Delta}) + s\bar{s}\sin(\theta_i - \theta_P)$$

ideal mixing angle $\theta_i = 35.3°$

no $s\bar{s}$ in the $\bar{p}p$ system:



θ_P : pseudoscalar mixing angle

From K, π, η, η' masses: $\theta_P = -24.5°$ (linear) , $-11.3°$(quadratic mass formula)

Prediction, for example:

$$\frac{B(\eta\eta)}{B(\eta\eta')} = \frac{(\sin^2\Delta)^2}{2(\sin\Delta\cos\Delta)^2} = \frac{\tan^2\Delta}{2}$$

(apart from phase space factors)

Ge85

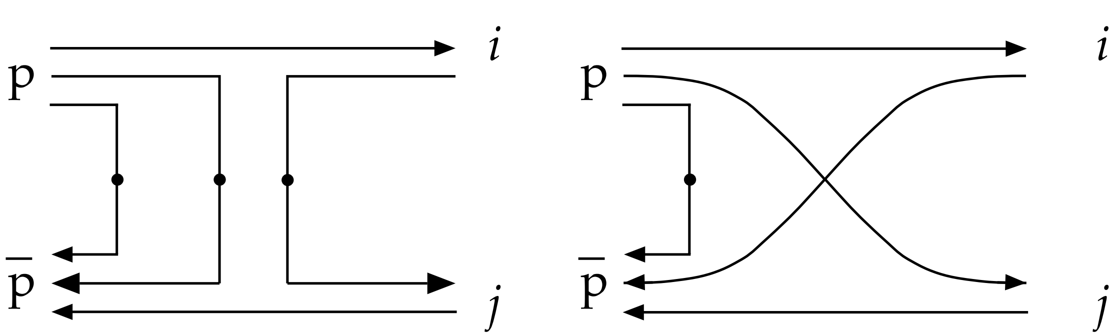
Calculate the pseudoscalar mixing angle:

Ratio	Prediction	θ_p (deg)
$\pi^0\eta/\pi^0\eta'$	$\tan^2(\theta_i-\theta_p)$	-18.1 ± 1.6
$\eta\eta/\eta\eta'$	$\frac{1}{2}\tan^2(\theta_i-\theta_p)$	-17.7 ± 1.9
$\omega\eta/\omega\eta'$	$\tan^2(\theta_i-\theta_p)$	-21.1 ± 1.5
$\eta\rho^0/\eta'\rho^0$	$\tan^2(\theta_i-\theta_p)$	$-25.4 \pm^{5.0}_{2.9}$

as expected, consistent results

Sign of quark dynamics

$i, j = u\bar{u}$ or $d\bar{d}$



A

Annihilation

no $u\bar{u}, d\bar{d}$

R

Rearrangement

no $d\bar{d}, d\bar{d}$

If A dominates: less consistent, contribution from R

e.g.

		θ_P (deg)
$\eta\rho^0/\omega\pi^0$	$\sin^2(\theta_i-\theta_p)$	-11.9 ± 3.2
$\eta'\rho^0/\omega\pi^0$	$\cos^2(\theta_i-\theta_p)$	-30.5 ± 3.5
$\eta\eta/\pi^0\pi^0$	$\sin^4(\theta_i-\theta_p)$	$-6.2 \pm^{0.6}_{1.1}$

$\rho^0\rho^0 = \omega\omega$ if A dominates

$$\rho^0\rho^0 = (1.2 \pm 1.2) \times 10^{-3}$$

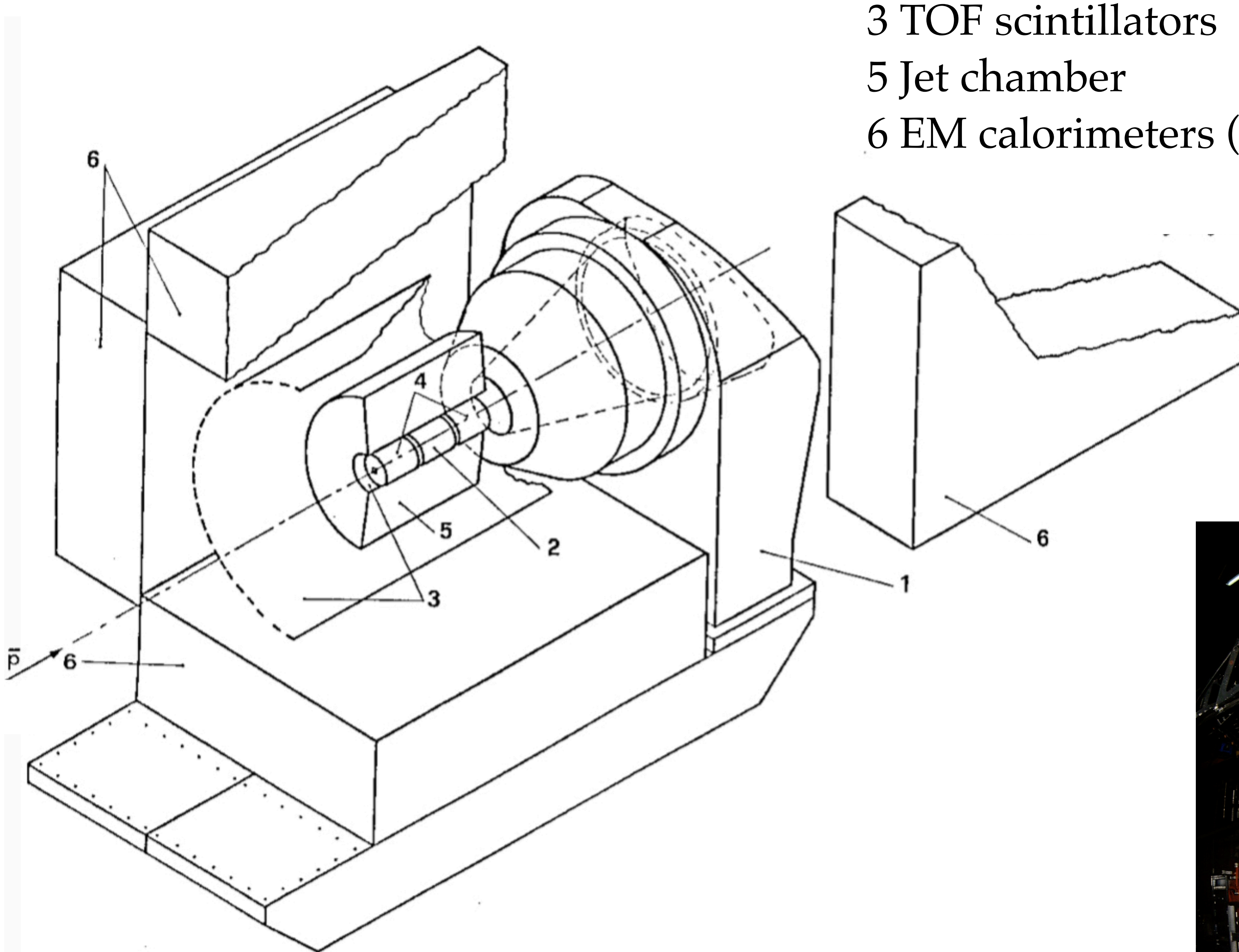
$$\omega\omega = (3.32 \pm 0.34) \times 10^{-2}$$

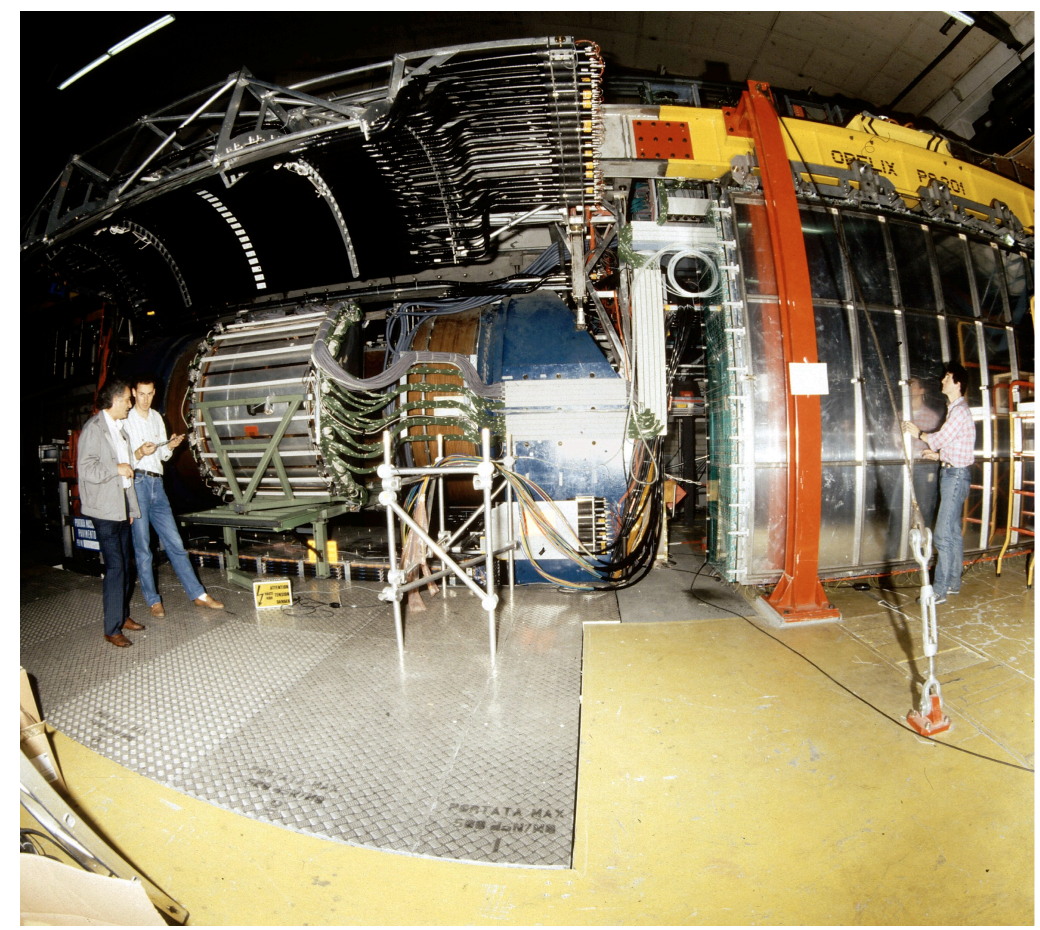
contribution from R

OBELIX

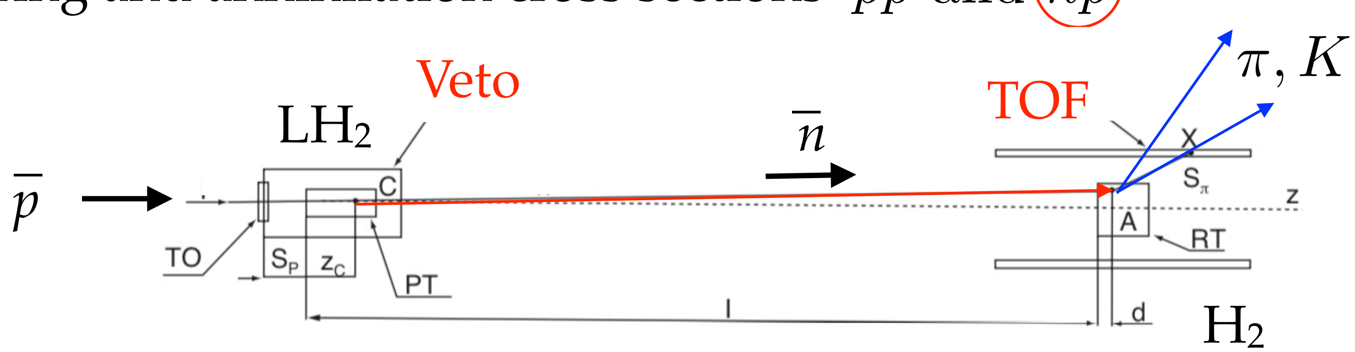
Br03

1 Open Axial Field Magnet (ISR) 6 kG @ center
3 TOF scintillators
5 Jet chamber
6 EM calorimeters (Pb-streamer tubes sandwich)





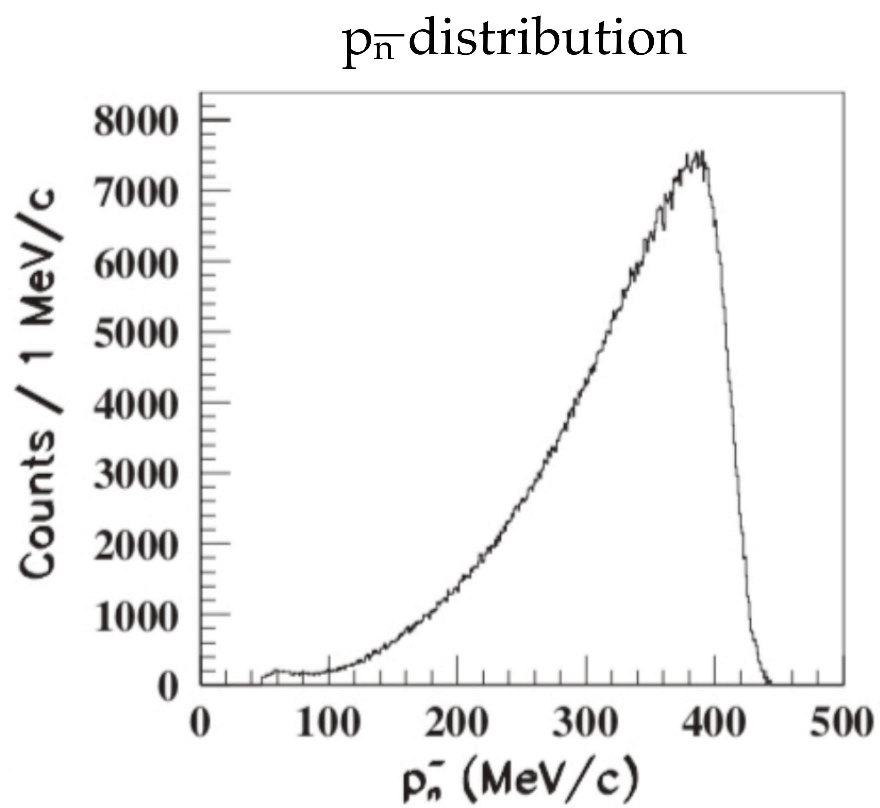
Scattering and annihilation cross sections $\bar{p}p$ and $\bar{n}p$



$\bar{p}p \to \bar{n}n$

412 MeV/c antiprotons
(minimum is 98 MeV/c)

Antineutron beam < 400 MeV/c



Bre03

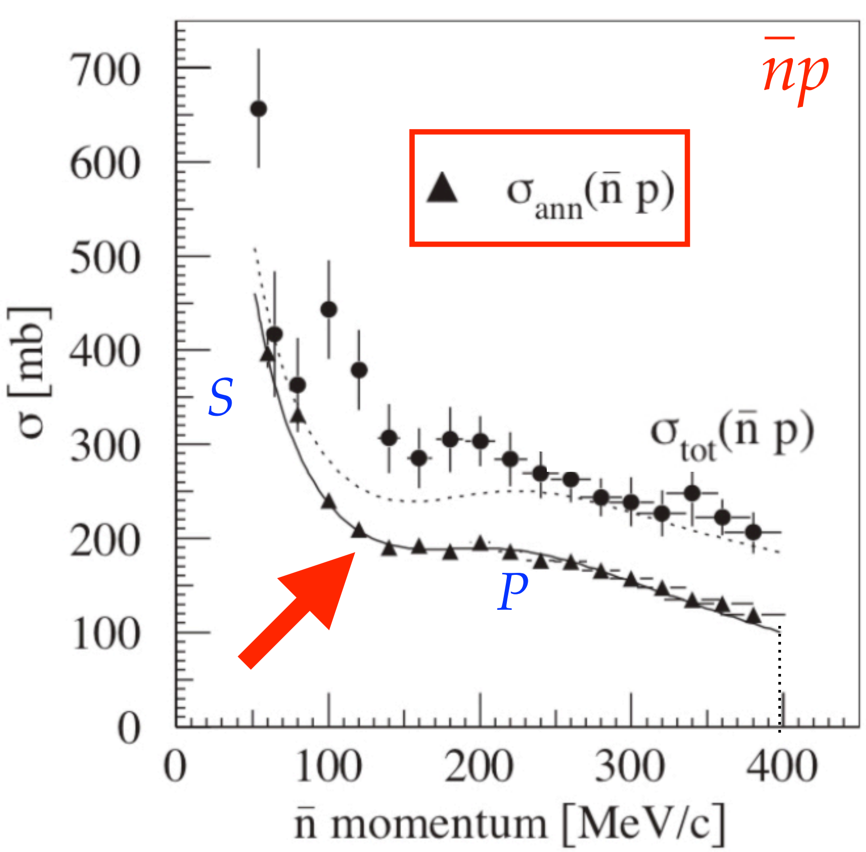
Advantages of low energy $\bar{n}$:

- no Coulomb interaction (for cross sections)
- no energy loss, no range straggling
- $\bar{n}p$ is isospin 1 only (fewer partial waves),
- no spectator compared to $\bar{p}n$ in $\bar{p}$-deuterium

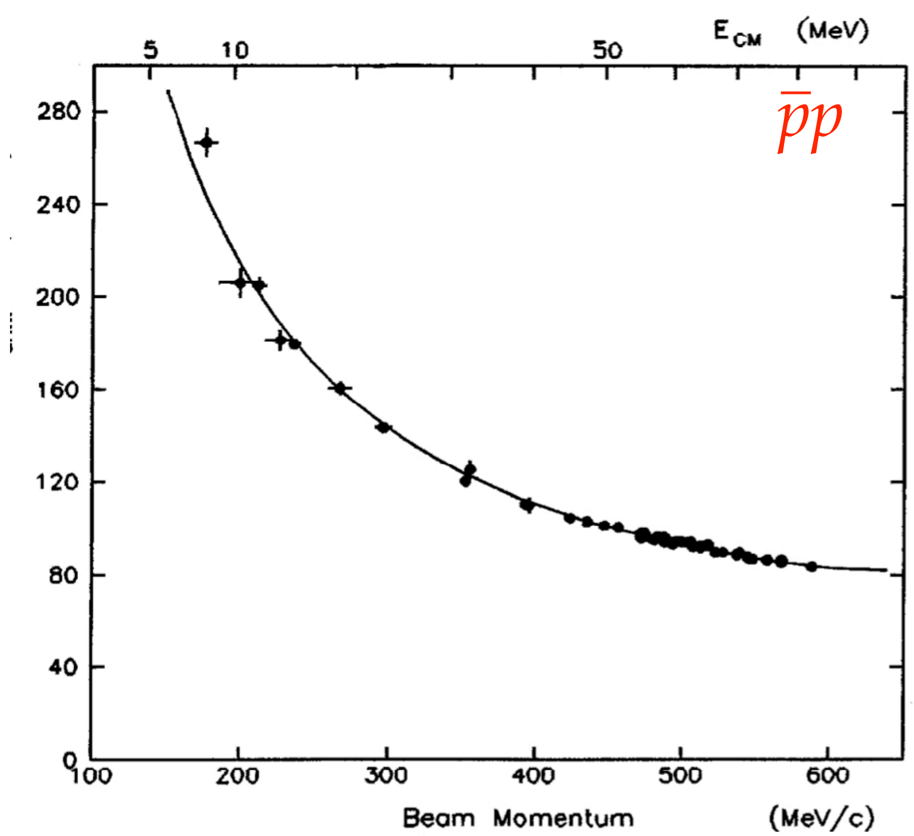
Disadvantages:

- uncertainty in the incident $\bar{n}\,(E)$ flux
- low flux (~40 $\bar{n}$ / 10^6 $\bar{\text{p}}$)

Annihilation cross sections



Bre03



Br90

- no resonances
- P-wave strong (attraction)
- $\sigma(\bar{n}p) \simeq \sigma(\bar{p}p)$

$\sigma(\bar{n}p) < \sigma(\bar{p}p)$

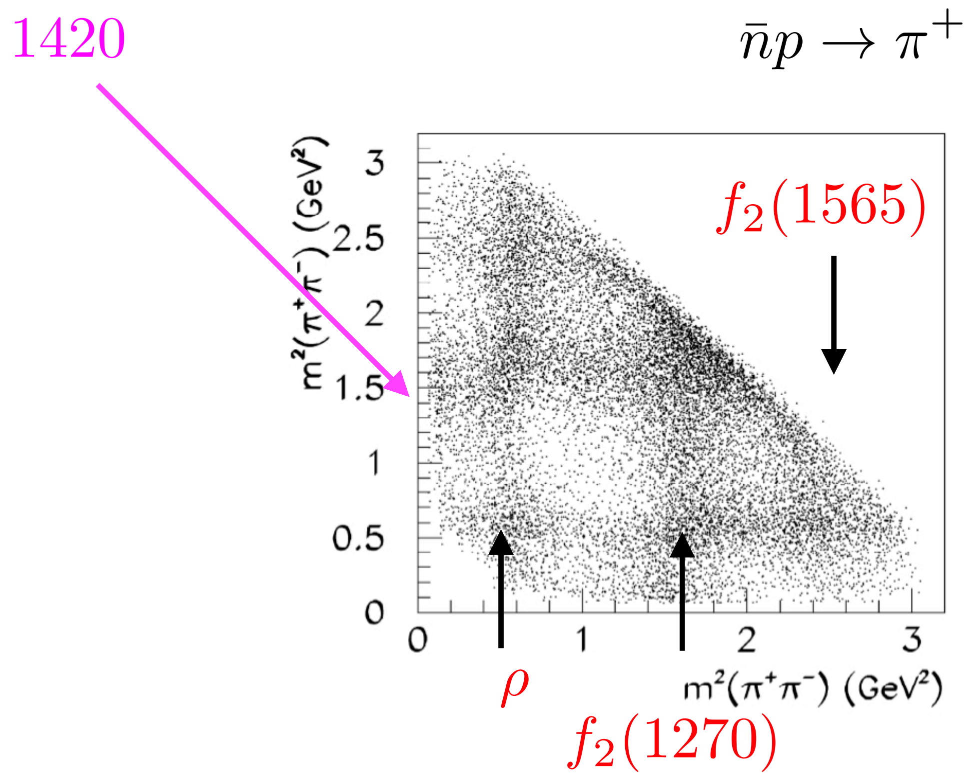
@ very low energy

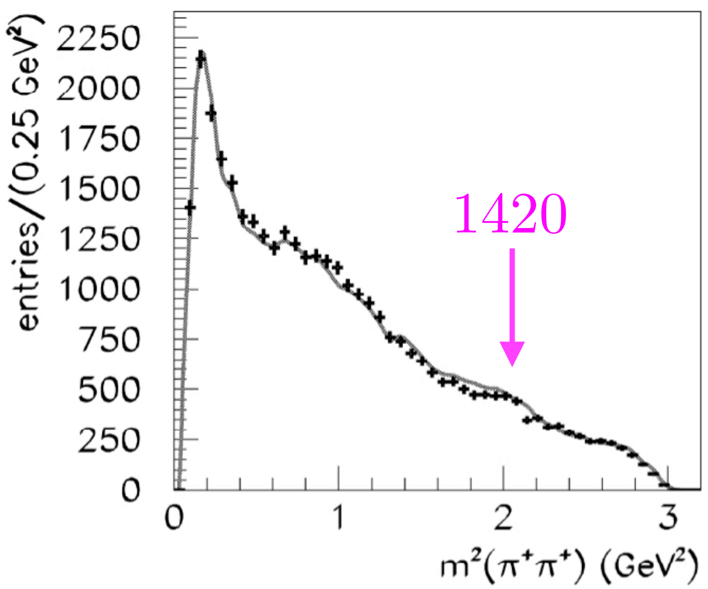
strong attraction in $I = 0$

Evidence for an $I = 2$ meson (OBELIX)

$\bar{n}p \to \pi^+\pi^-\pi^+$

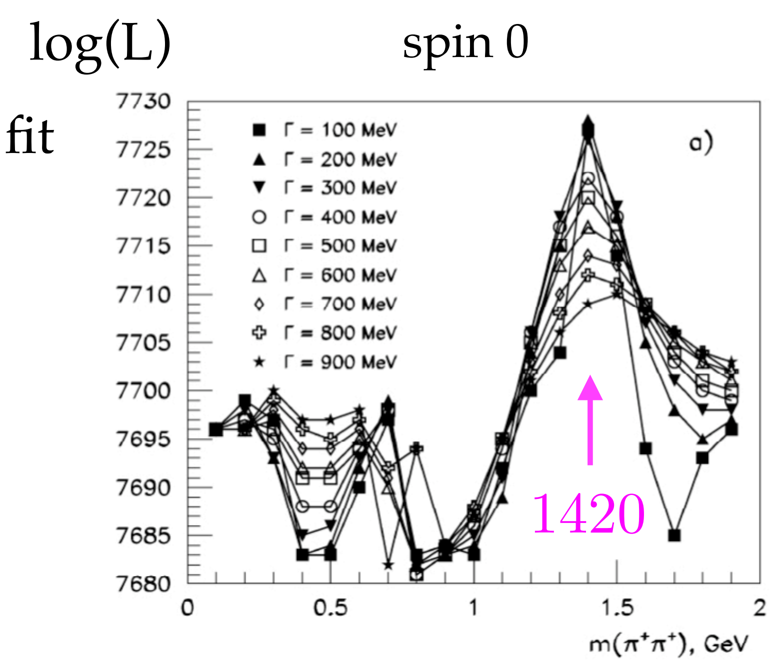
Fi00





35'118 events

Dalitz plot fit



$M = 1420 \pm 20, \Gamma = 100 \pm 10$ MeV $\qquad J^{PC}(I^G) = 0^{++}(2^+)$

I= 2: not a quark-antiquark state (tetraquark?)

Violation of the OZI rule

As before:

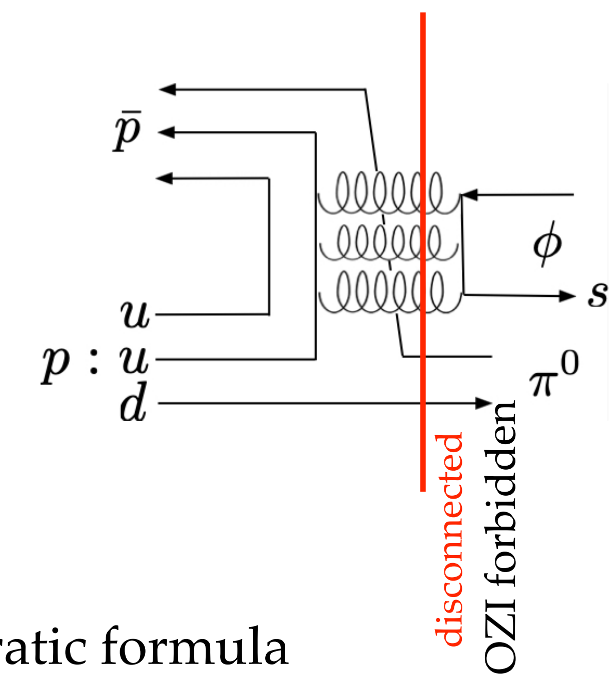
$$\phi = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin(\theta_i - \theta_V) - s\bar{s}\cos(\theta_i - \theta_V)$$

$$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos(\theta_i - \theta_V) + s\bar{s}\sin(\theta_i - \theta_V)$$

θ_V : vector mixing angle

From K^*, ρ, ω, ϕ masses: 36.5° (linear) 39.2° (quadratic mass formula) $\theta_i = 35.3°$

decoupling $\phi \simeq -s\bar{s}$ $\omega \simeq \frac{1}{\sqrt{2}}(d\bar{d} + u\bar{u})$



Assuming no $s\bar{s}$ in the nucleon: OZI rule suppresses ϕ production

e.g. $\phi\pi^0$

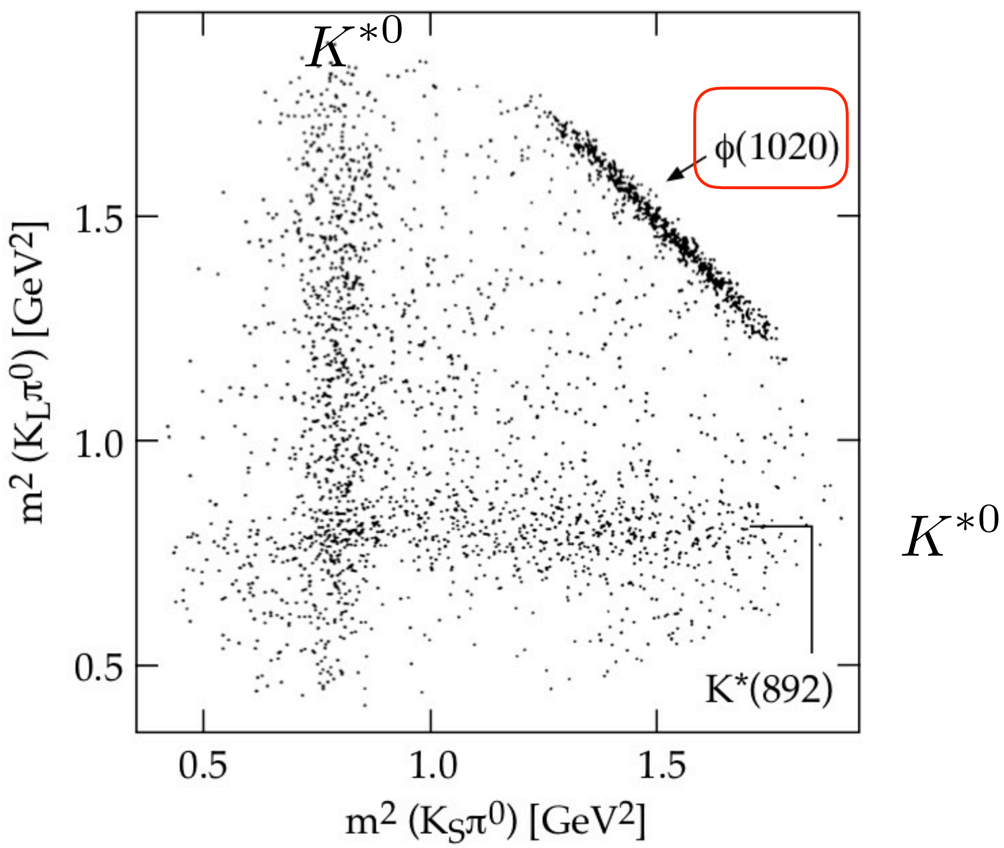
Apart from phase space factors $\frac{B(\phi X)}{B(\omega X)} = \tan^2(\theta_V - \theta_i)$ $= 5 \times 10^{-3}$ quadratic formula

e.g. $\omega\pi^0$

(even smaller with linear formula)

Crystal Barrel @ rest

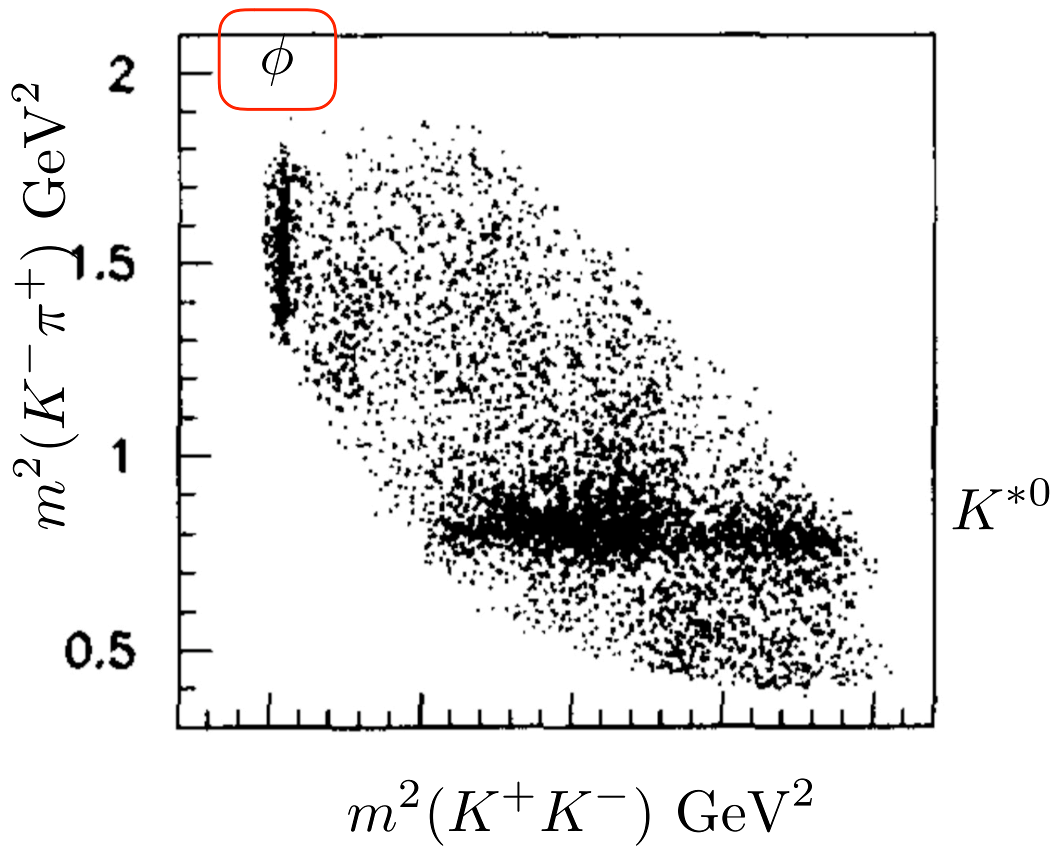
$\phi\pi^0 : \bar{p}p \to K_S K_L \pi^0 \to 3\pi^0 + \text{miss} K_L$



Am93

OBELIX, $\overline{\text{n}}$ momentum < 405 MeV/c

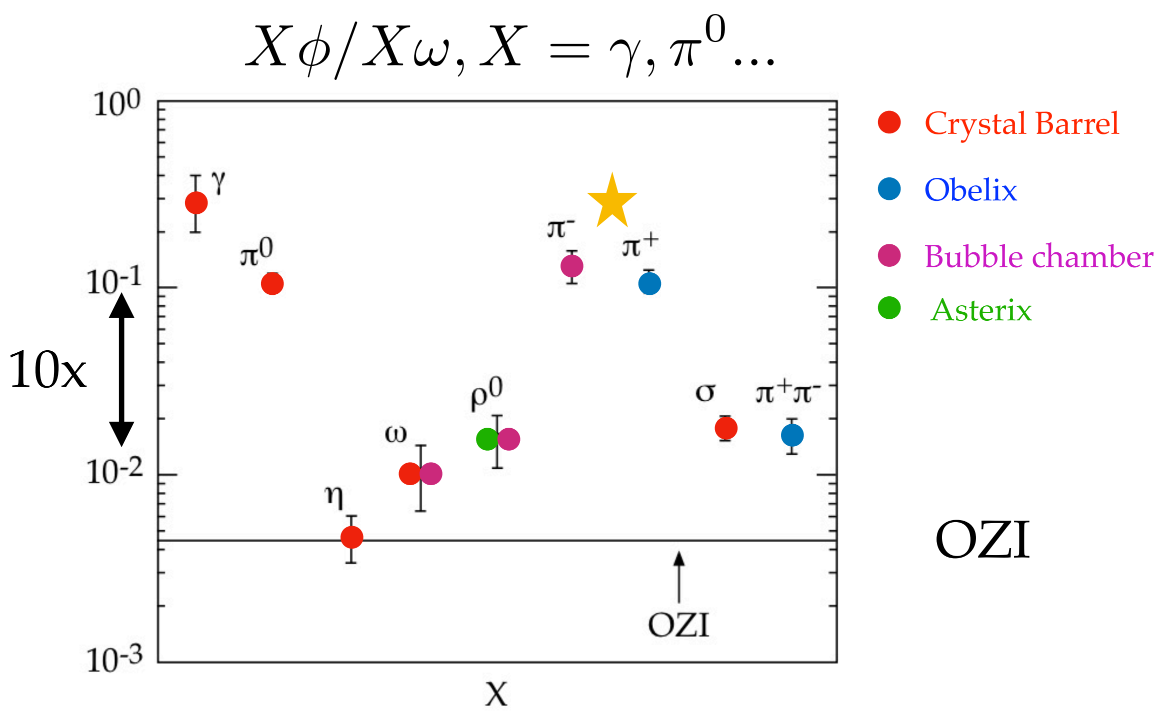
$\phi\pi^+ : \bar{n}p \to K^+ K^- \pi^+$



Fi99,Br03

Compare with $\omega\pi^0 : \bar{p}p \to \omega\pi^0 \to \gamma 2\pi^0$

$\omega\pi^+ : \bar{n}p \to \pi^+\pi^-\pi^0\pi^+$



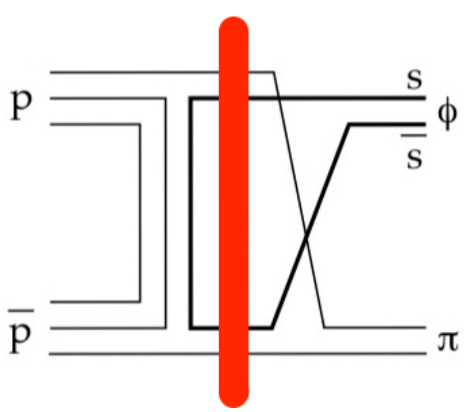
Very large OZI violation at rest with almost any X in liquid H_2 (and low energy $\overline{p}, \overline{n}$) ★ RMP98

Very large $\gamma\phi$ Lo94

OZI

Possible explanations: for example for $\phi\pi$ $({}^3S_1\ \bar{p}p)$ 1^{--}

① $sq\bar{s}\bar{q}$ tetraquark states? DoFi89



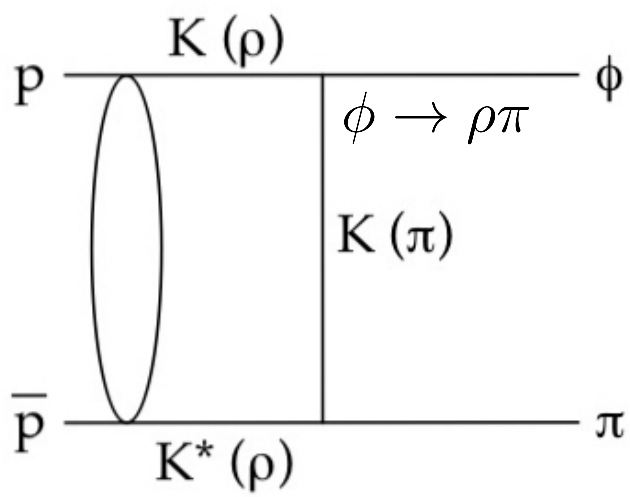
No violation of OZI rule

close to $N\overline{N}$ threshold, 1^{--} candidates near $2m_p$...:

e.g. C(1480) in $\pi^- p \to Cn, C \to \phi\pi^0$ Serpukhov, $\omega\pi^0$ not seen Bi87

or $\phi(2170) \to \phi\pi\pi$ well established meson

② Rescattering



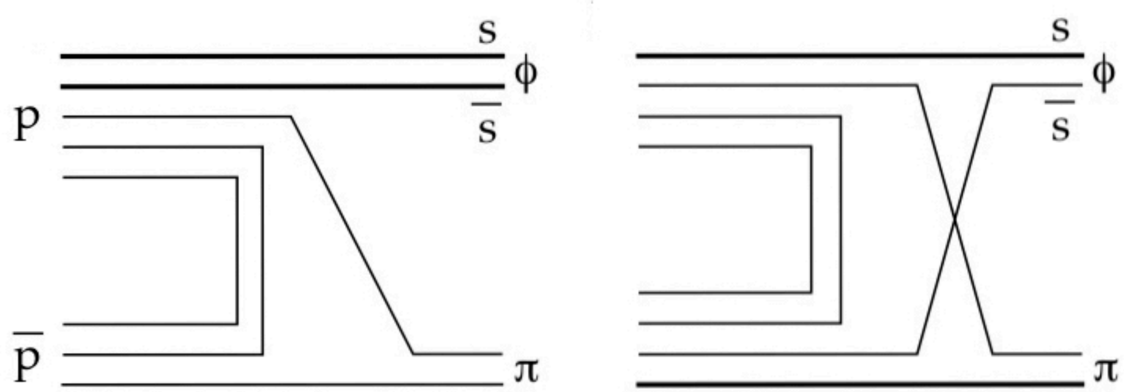
Constructive interference between

$K^*\bar{K}$ and $\rho\rho$ → large $\phi\pi$ Go96

③ Strange sea quarks in the nucleon:

Deep inelastic scattering with muons: $s\bar{s}$ spins parallel and opposite to nucleon spin El95

$\bar{s}s$ spins parallel opposite to $p\bar{p}$ $^3S_1$ (as needed for the spin 1 ϕ)

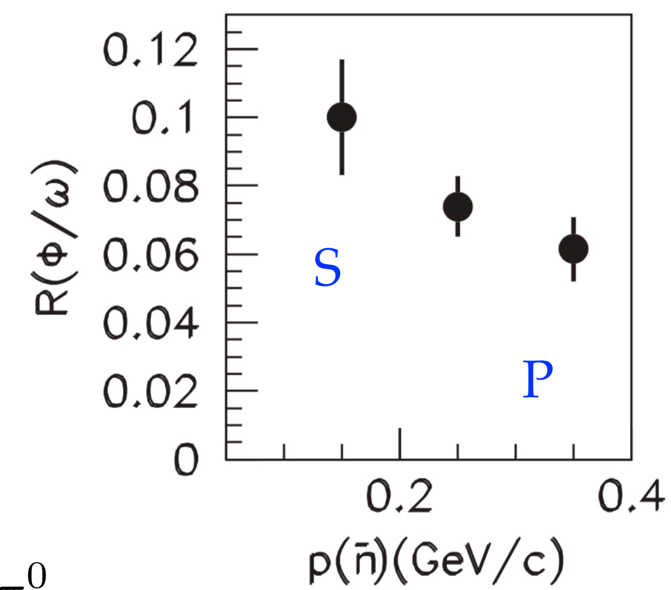


wavefunction does not match OK

- Should be strong in S-wave, weak in P-wave (spin singlet $^1P_1 \to \phi\pi$)

Yes!

Antineutrons (OBELIX)



$\phi\pi/\omega\pi$

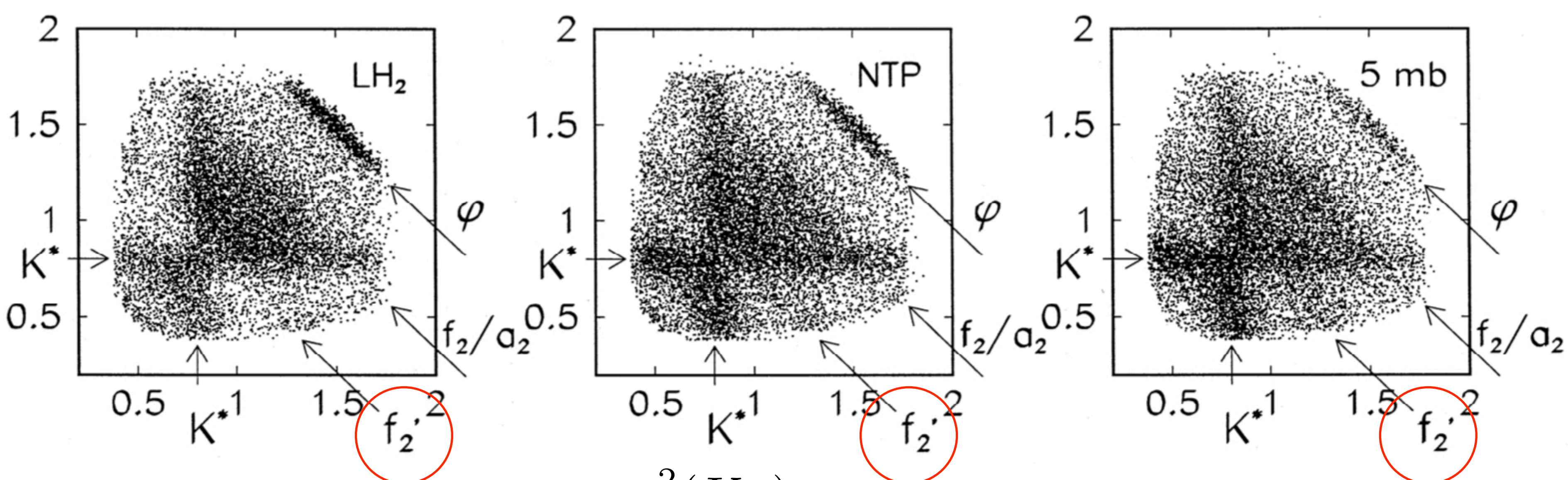
Br03

- $\underbrace{f_2'}_{}(1525)\pi^0$ should be too strong in P-wave compared to $\underbrace{f_2}_{}(1270)\pi^0$

$J = 2$ (spin triplet $s\bar{s}$) $u\bar{u} + d\bar{d}$

$\bar{p}p \to K^+K^-\pi^0$ OBELIX at rest

from S waves NTP from P waves



$m^2(K\pi)$

ϕ decreases while $f_2'(1525)$ increases

$$\frac{f_2'\pi^0}{f_2\pi^0} = 0.149 \pm 0.020$$

from P-waves expect 0.016!

Al98

Pontecorvo (1956) reactions

Unusual, involve > 1 nucleon

$$\bar{p}d \to \pi^- p, \pi^0 n, \eta n, \omega n, \eta' n, \phi n, \rho^- p$$

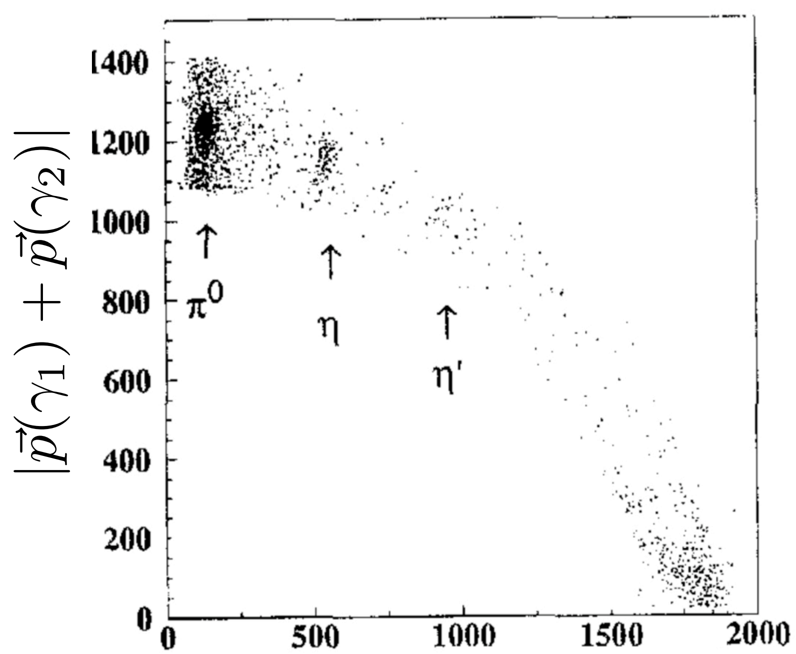
$$\bar{p}d \to \Delta^0 \pi^0, \Delta^+ \pi^-, \Lambda K^0, \Sigma^0 K^0$$

Obtained at LEAR, typical rates 10^{-6} to 10^{-5}

Be94, Ab99, Am95, Ab94, Go02

Example: (1) $\bar{p}d \to \pi^0 n, \eta n, \eta' n \to 2\gamma n$ Crystal Barrel

200 MeV/c beam, LD_2 target, 4 million 0-prong trigger (rare reaction!), neutron not detected



$m(\gamma_1, \gamma_2)$ [MeV]

Am95

search in min. bias and normalize to $\bar{p}d \to \pi^0 \pi^0 n$

$B \quad (\bar{p}d \to \pi^0 n) =$

$(7.02 \pm 0.72) \times 10^{-6}$

x 2

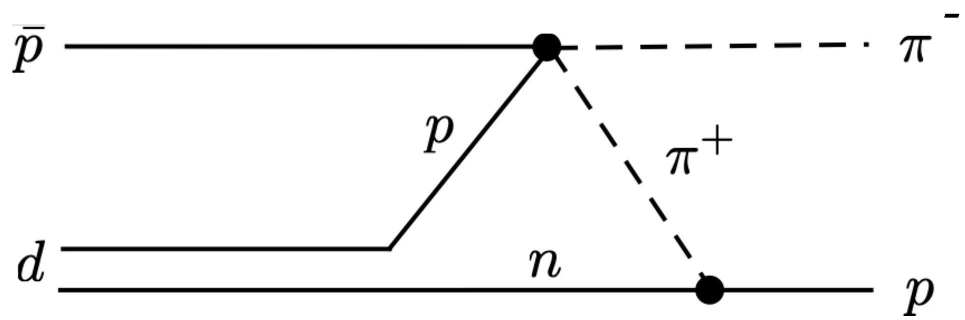
$B \quad (\bar{p}d \to \pi^- p) =$

$(1.41 \pm 0.14) \times 10^{-5}$

$\bar{p}d \to \eta n \quad (3.19 \pm 0.48) \times 10^{-6}$

$\bar{p}d \to \eta' n \quad (8.2 \pm 3.4) \times 10^{-6}$

Rescattering

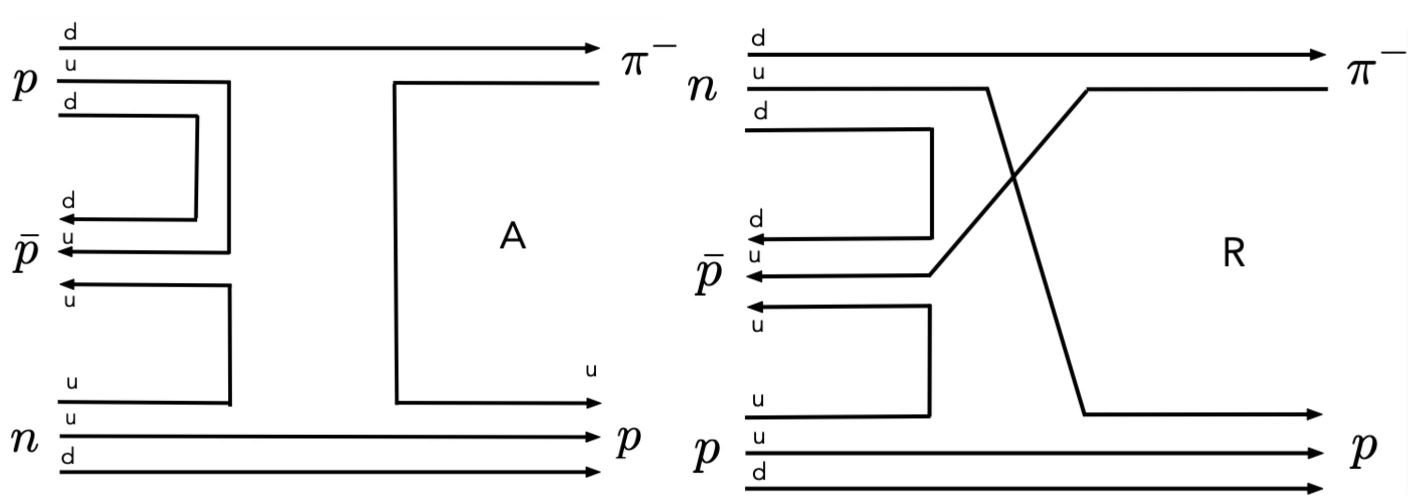


Predictions uncertain: 4 - 12 x 10^{-5}

- depending on N$\bar{\text{N}}$ potential, short distance uncertain Os89
- deuteron wave function, meson form factors 10^{-6} - 10^{-3} Ko89

Fireball model (see next slide) Cu84, 89

Fireball production $3\bar{q}$, 6q bag
which decays hadronically, presumably via



② $\bar{p}d \to \Lambda K^0, \Sigma^0 K^0$

$\Sigma^0 \to \Lambda\gamma$

$\boxed{\Lambda \to p\pi^-}$

K^0 : K_S or K_L

$K_S \to \boxed{\pi^+\pi^-}$, K_L: not detected

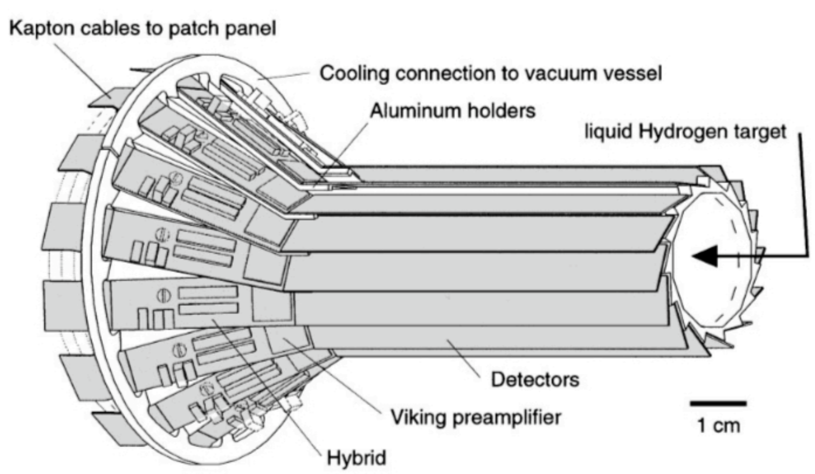
2 prongs or 4 prongs

Crystal Barrel

Between microstrips and drift chamber:

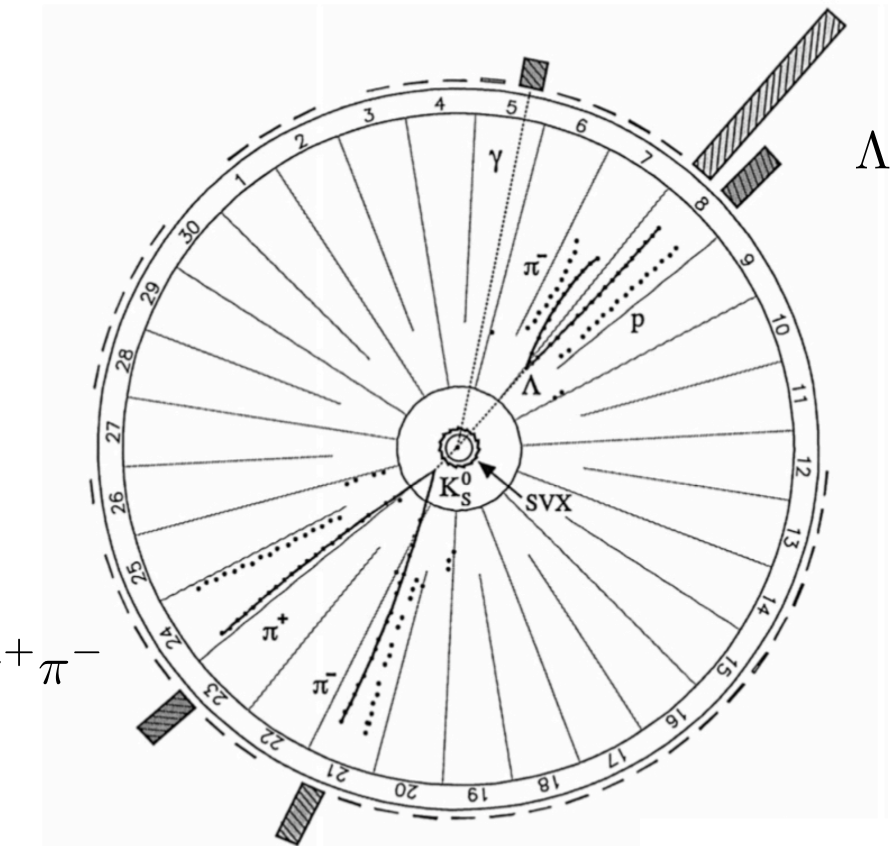
$n_{\pm} = 0$ -> 2 or 4

add a microstrip detector:



15 µstrips, pitch 50 µm,

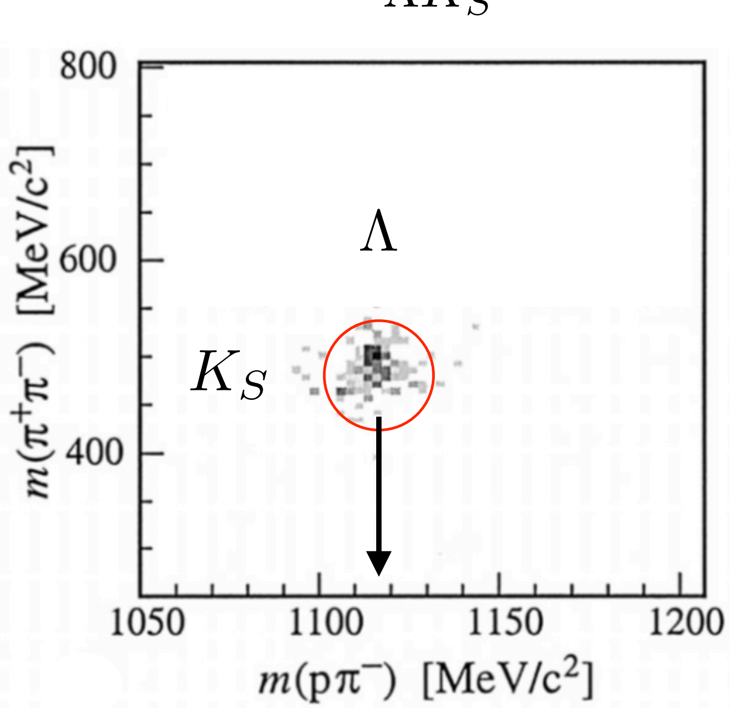
$\Lambda \to p\pi^-$



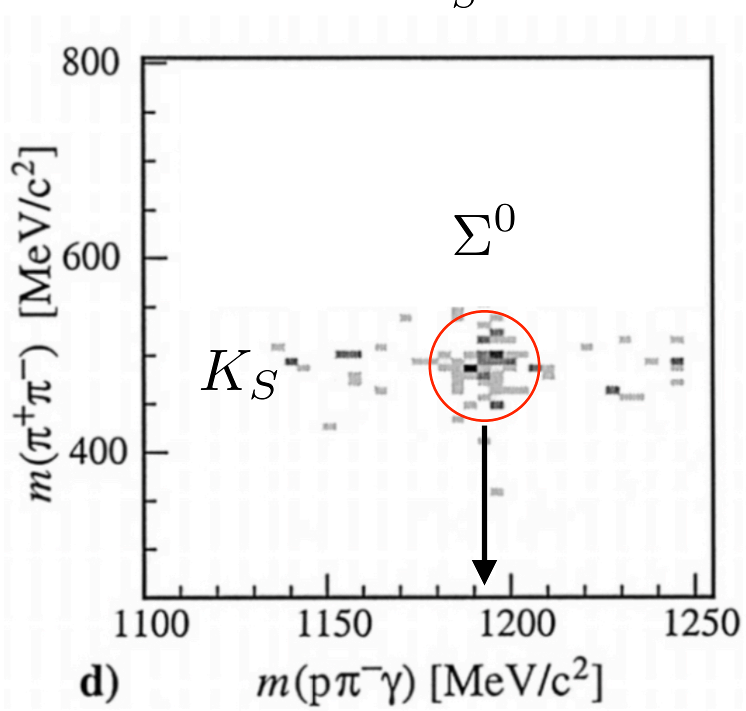
$K_S \to \pi^+\pi^-$

Do98

ΛK_S



$\Sigma^0 K_S$

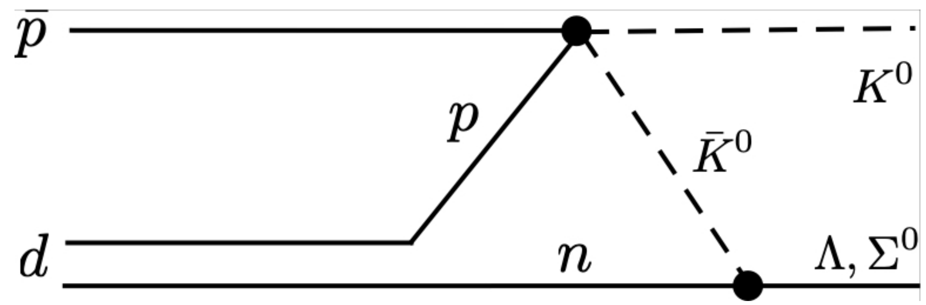


ΛK^0	$(2.35 \pm 0.45) \times 10^{-6}$
$\Sigma^0 K^0$	$(2.15 \pm 0.45) \times 10^{-6}$

equal branching ratios

Ab99

Rescattering?



~10^-7^ $\neq$ ~10^-9^ — too small — Ko89, He89

Λ Σ^0

$\neq$ $g(KN\Lambda) >> g(KN\Sigma)$

due to $\Lambda(1405)$

Fireball:

- $\overline{\text{p}}$N: annihilation in agreement with phase space weights with annihilation branching ratios for

$$\bar{p}p \to \text{ pions, kaons}$$

- $\overline{\text{p}}$2N annihilation: rate = probability P to form fireball x phase space factor — Cu84, 89

$$B(\bar{p}d \to \pi^- p) = P \times \underbrace{4.7 \times 10^{-4}}_{\text{phase space factor}} \Rightarrow \boxed{P = 3\%}$$

then $B(\bar{p}d \to \Lambda K^0, \Sigma^0 K^0) = 3\% \times \underbrace{\text{phase space}}_{\sim 10^{-4}} (\Lambda K^0, \Sigma^0 K^0) = \boxed{3 \times 10^{-6}}$ and both channels ~equal

Data: $(2.35 \pm 0.45) \times 10^{-6}$ ΛK^0

$(2.15 \pm 0.45) \times 10^{-6}$ $\Sigma^0 K^0$ — OK!

- Future check: $\overline{\text{p}}$3N annihilation

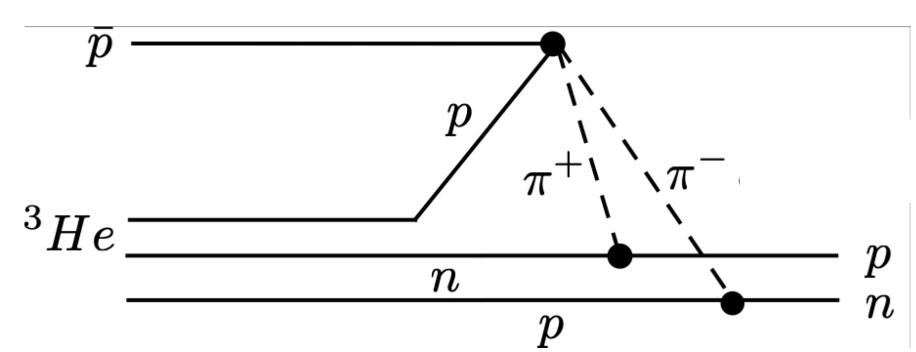
$\bar{p}^3He \to np$

$\bar{n}^3He \to pp$

fireball prediction: ~10^-6^

much larger than for rescattering (10^-8^ - 10^-7^)

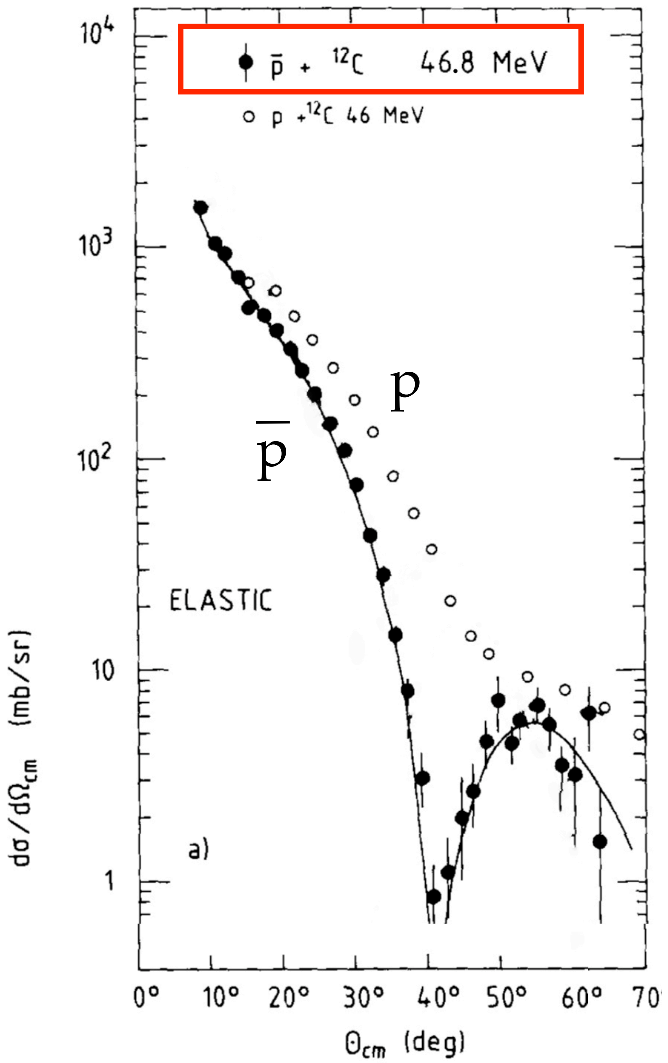
Ko88



Antiproton annihilation on the nucleus

Gu89
Be94

(Striking features from a non-expert, see review of v. Egidy Eg87)



PS184: SPESII spectrometer

Ga84

Black sphere

Annihilation successfully described
by Intranuclear Cascade model (INC), Liège model

INC

- on one nucleon at the surface @ 10% of nuclear density,
low multiplicity, 350 MeV/c average pion momentum

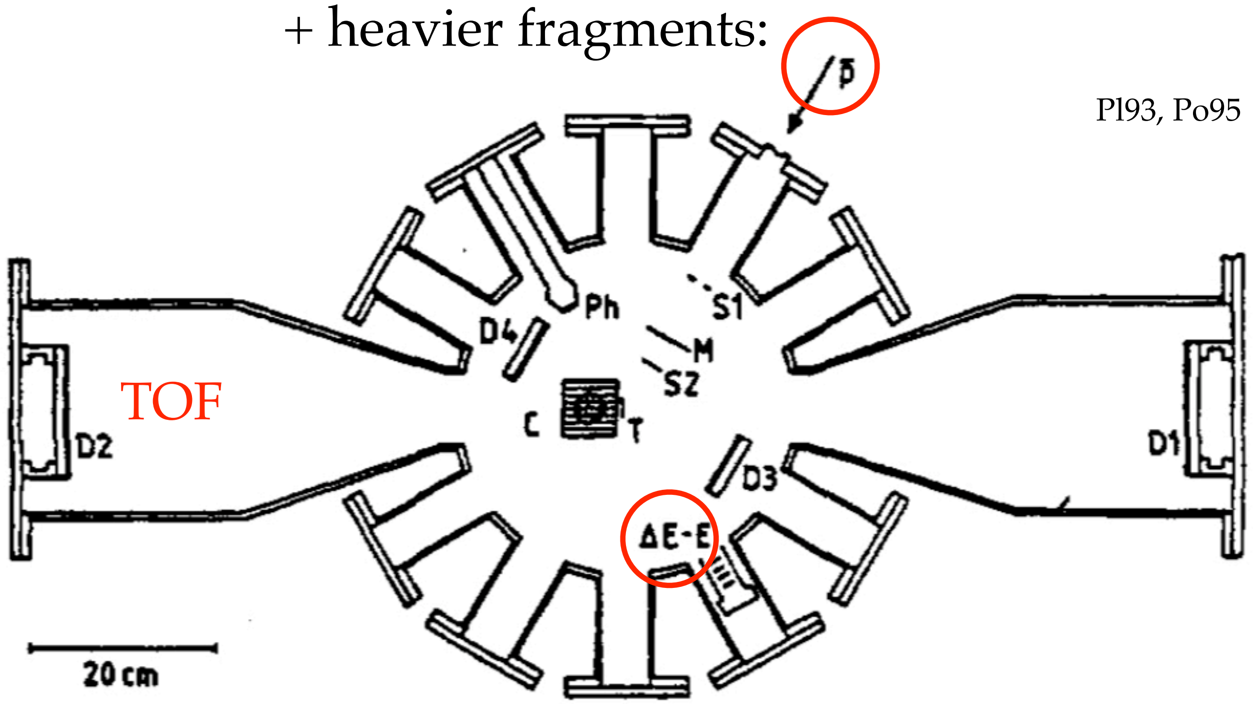
- by pion rescattering, short range (Δ resonance)
localized deposit, nuclear fragments, deeper inside, high multiplicity

- more neutron emission than N/Z (LEAR PS203), not explained in INC

Po95

PS186, 203 p, d, t, ^{4}He, ^{3}He from Li to U, 20 -180 MeV
+ heavier fragments:

Pl93, Po95



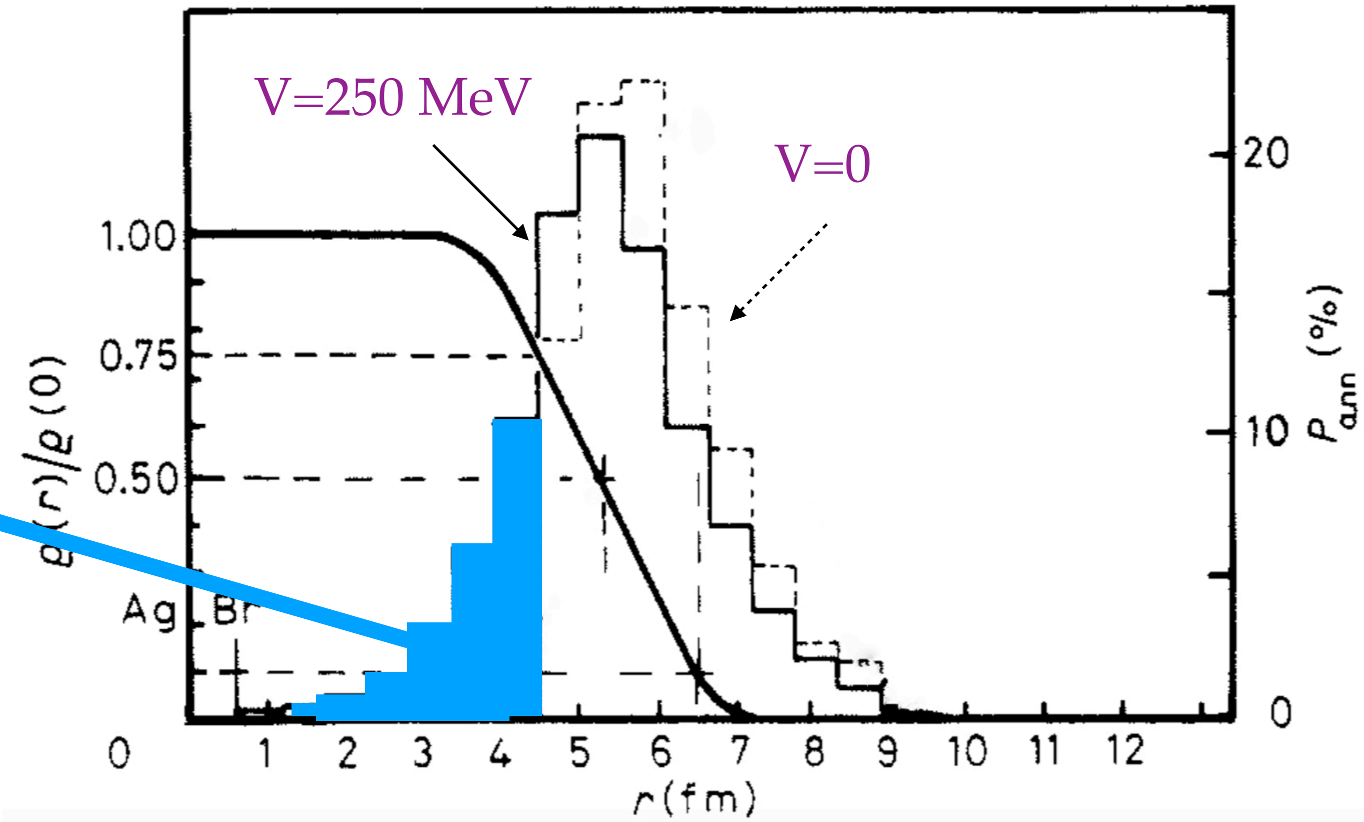
- Annihilation on the surface: AgBr (emulsions), LEAR 0-500 MeV/c (PS179) Ba86

$\bar{p}$ momentum (MeV/c)	$(M < 10)$ (%)	$(M \geqslant 10)$ (%)
at rest	93 ± 1	7 ± 1
300	71 ± 5	29 ± 5
400	74 ± 4	26 ± 4
500	72 ± 4	28 ± 4

surface interior

High multiplicity from the interior

Annihilation probability:



590 MeV/c (on U) Cl82

- Evidence for a neutron halo: BNL experiment stopped antiprotons (BNL 1973) Bu73

Target in BBC, measure odd/even number of prongs

More annihilation on neutrons than expected from N/Z

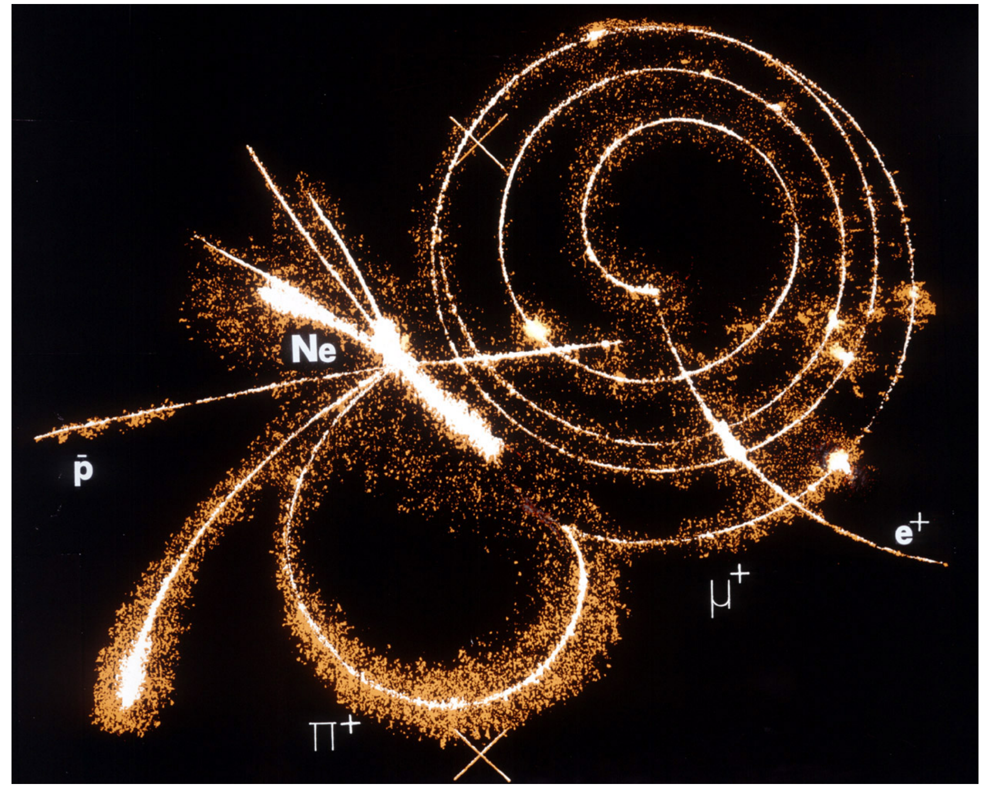
Factor 6 from C to Pb

- Nothing unusual in the production of strangeness (such as an enhancement due to quark-gluon plasma) ~ 6.2 % kaons at rest and 400 - 900 MeV/c (ITEP Xe BBC), INC: 6.25% at 650 MeV/c!

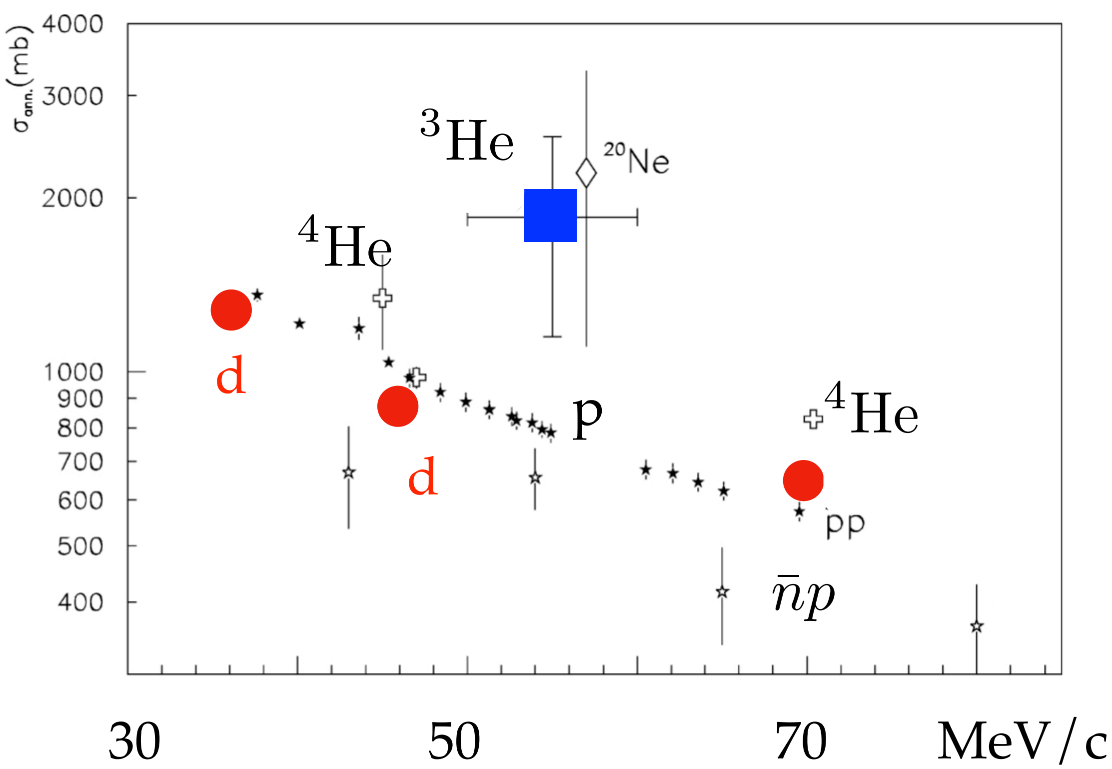
Hyperon production through e.g. $\bar{K}N \rightarrow \Lambda\pi$ Dol91

- Streamer chamber (PS179)

$\bar{p}$Ne



Annihilation cross sections:



Bi00

d < p   p in the shadow of the n

^{20}Ne $\simeq$ ^{3}He   Coulomb focussing?

^{3}He > ^{4}He

Summary

Global annihilation process in fair agreement with statistical distribution
Details are not well understood, e.g. $K\bar{K}$ suppression from P-states, $\rho\pi$ puzzle
Evidence that quarks play an important role, e.g. leading to correct pseudoscalar mixing angle

Reason for the strong violation of OZI rule is not clear, sea (anti)quarks in the (anti)nucleon?
Pontecorvo reactions are best explained by the fireball model

Gas density changes the spectroscopy (50:50 S:P at rest NTP H_2 gas)
Several new mesons have been observed at low energy $\bar{p}p$ and $\bar{n}p$, tetraquark, baryonium (1), glueball (?)

Prospects:

- investigate $\bar{p}p$ and $\bar{n}p$ in flight below 200 MeV/c: FLAIR @ GSI
- annihilation at rest at ELENA (e.g. check Pontecorvo reaction $\bar{p}$3N):
  Need DC beam: e.g. trap with ELENA 10^6 $\bar{p}$ per AD spill
  then release 10^4/s during 100s AD cycle, solid H_2 target

Dec 1994

Physics World December 1994 3

PHYSICS *world*

Annihilation that should be postponed

Two years from now a unique experimental facility is due to be closed. Already the physicists who use it are allowing good ideas to atrophy in anticipation of its loss. The owners of the facility appear to have terminated all consideration of an extension and, because of political sensitivities, their employees are uncharacteristically reticent when asked to discuss the issue. But need it end this way?

The facility is the Low Energy Antiproton Ring (LEAR) at CERN, which emerged as a by-product of the proton–antiproton collider that was used in the first detections of the W and Z bosons. High-energy protons generated by CERN's proton synchrotron strike a target that produces antiprotons at several GeV, which, in a series of steps, can be decelerated and then stored in LEAR at energies of a few MeV. (This summary glosses over an extraordinary engineering achievement which helped to win Simon van der Meer a share of the 1984 Nobel prize.) Antiprotons extracted from LEAR can be decelerated further to kinetic energies of meV. There is no other facility in the world that provides antiprotons at such low energies.

What are they good for? Three topics within the LEAR programme are generating particular interest. One concerns measurements of the decay products of proton–antiproton collisions, amongst which, theorists are now saying, bound states of gluons ("glueballs") seems likely to have been detected. More generally, LEAR provides a unique probe of still-mysterious aspects of the Standard Model describing gluon behaviour. Second, experiments exploring CP violation provide an important complement to those being carried out in more conventional accelerators. And third, results published earlier this year – more esoteric but certainly of interest to atomic physicists – have illuminated the origin of the unexpectedly long life (microseconds) of antiprotonic helium atoms. Such atoms are formed by the capture of an antiproton by a He^{+} ion prior to annihilation.

The principle reason for the planned closure of LEAR is the Large Hadron Collider, currently awaiting approval by CERN's member states. In practice there is no strong technical reason why LEAR should not continue for several years more – the LHC itself is unlikely to be completed before 2002. But the decision to forego LEAR and other aspects of CERN's experimental programme in order to focus the laboratory's constrained resources on the LHC is nevertheless arguably justifiable. Nobody would claim, on current expectations, that LEAR's physics programme is as fundamentally significant as that of the LHC. More relevantly, CERN has to respond to the demands of member states by prioritizing to keep costs to an absolute minimum.

The fact remains that physicists from several countries (including non-member states such as the US) have a need for LEAR's unique facilities. CERN's announcement that LEAR will have to go if the LHC is approved has already led to planning blight. But gluon and anti-atom explorations deserve a brighter future.

If CERN's controversial sense of priorities is accepted, LEAR's physicists have only one option: to explore whether LEAR can be reformulated as a distinct, multilaterally funded facility sited at CERN. There are no easy ways of achieving this and no precedents. But, as organizations such as the OECD and the European Science Foundation are demonstrating, that route would be entirely in the spirit of today's ever more international approach to funding.

References

Ab94 V.G. Ableev et al., Nuov. Cim. 107(1994) 2837

Ab99 A. Abele et al., Phys. Lett. B 469 (1999) 276

Ah85 S. Ahmad et al., Phys. Lett. B 152 (1985) 135

Ah85b S. Ahmad et al., , Phys. Lett. B 157 (1985) 333

Ah90 S. Ahmad et al., Nucl. Instr. Meth. A286 (1990) 76

Al98 A. Alberico et al., Phys. Lett. B438 (1998) 430

Am92 C. Amsler et al., Phys. Lett. B 297 (1992) 214

Am93 C. Amsler et al., Phys. Lett. B 319 (1993) 373

Am95 C. Amsler et al., Z. Phys. A351 (1995) 325

Am96 C. Amsler and F.E. Close, Phys. Rev. D 53 (1996) 295

AMy C. Amsler, F. Myhrer, Ann. Rev. Nucl. Part. Sci. 41 (1991) 219

Ar69 see e.g. R. Armenteros and B. French, 1969, in $N\bar{N}$ Interactions in High Energy Physics, ed. by E. H. S. Burhop (Academic, New York), Vol. 4, p. 237; J. Diaz et al., Nucl. Phys. B16 (1970) 239

Ba86 Y.U. Batusov et al., Europhys. Lett. 2 (1986) 115

Ba89 C. J. Batty, Rep. Prog. Phys. 52 (1989) 1165

Ba96 C. J. Batty, Nucl. Phys. A 601 (1996) 425

Be77 P. Benkheiri et al., Phys. Lett. 68B (1977) 483

Be94 G. Bendiscioli and D. Kharzeev, Rev. Nuov. Cim. 17 (1994) 1

Bi87 S.I. Bityukov et al., Phys. Lett. B 188 (1987) 383

Bi00 A. Bianconi et al., Phys. Lett. B 492 (2000) 254

Br03 T. Bressani, A. Filippi, Phys. Rep. 383 (2003) 213

Br77 W. Brückner et al., Phys. Lett. 67B (1977) 222

Br90 W. Brückner et al., Z. Phys. A 335 (1990) 217

Bu73 W. M. Bugg et al., Phys. Rev. Lett. 31 (1973) 475

Ca18 C. Amsler, Lecture Notes in Physics 949, Springer (2018)

Ca87 C. Amsler, Adv. Nucl. Phys. 18 (1987) 183

Cl82 M. R. Clover et al., Phys. Rev. C26 (1982) 2138

Cu84 J. Cugnon, J. Vandermeulen, Phys. Lett. 146B (1984) 16

Cu89 J. Cugnon, J. Vandermeulen, Phys. Rev. C39 (1989) 181

Dol91 A. Dolgolenko et al., in K. Holinde et al., First Biennial Conf. on Low Energy Antiproton Physics, ed. P. Carlson et al., World Scientific (1991) p 205

Do79 C.B. Dover and J.M. Richard, Ann. Phys. 121 (1979) 70

Do88 M. Doser et al., Phys. Lett. B 215 (1988) 792

Do88b M. Doser et al., Nucl. Phys. A486 (1988) 493

Do98 M. Doser et al., Nucl. Instr. Meth. in Phys. Res. A 412 (1998) 70

DoFi89 C.B. Dover and P.M. Fishbane, Phys. Rev. Lett. 62 (1989) 2917

Eg87 T. von Egidy, Nature 328 (1987) 773

El95 J. Ellis et al., Phys. Letters B353 (1995) 319

Fe77 E. Fett et al., Nucl. Phys. B130 (1977) 1

Fi00 A. Filippi et al., Phys. Lett. B 495 (2000) 284

Fi99 A. Filippi, et al., Nucl. Phys. A 655 (1999) 453

Fo68 M. Foster et al., Nucl. Phys. B6 (1968) 107

Ga83 D. Garreta et al., Phys. Lett.135 B (1984) 266

Ge85 H. Genz, Phys. Rev. D31 (1985) 1136

Gh74 C. Ghesquière, 1974, in Antinucleon-Nucleon Interactions, Proceedings of the Liblice Symposium, CERN Yellow Report No. 74-18, p. 436

Go02 O.E. Gorchakov et al., Phys. Lett. B 528 (2002) 34

Go96 O. Gortchakov et al., Z. Phys. A353 (1996) 447

Gu89 C. Guaraldo, Nuov. Cim. 102 A (1989) 1137

He89 E. Hernandez, E. Oset, Phys. Lett. B 226 (1989) 223

INC J. Cugnon, J. Vandermeulen, Annales de Physique 14 (1989) 49

Ki81 M. Kimura and S. Saito, Nucl. Phys. B178 (1981) 477

Kl05 E. Klempt, C. Batty, J.M. Richard, Phys. Rep. 413 (2005) 197

Ko88 L.A. Kondratyuk and M.G. Sapozhnikov, Physics at LEAR with Low Energy Antiprotons, edited by C. Amsler et al. (Harwood-Academic, New York, 1988), p 771.

Ko89 L.A. Kondratyuk, M.G. Sapozhnikov, Phys. Lett. B 220 (1989) 333

Lo94 M. Locher et al., Z. Phys. A347 (1994) 281

Ma90 B. May et al., Z. Phys. C46 (1990) 191, 203

Os89 E. Hernandez, E. Oset, Nucl. Phys. A494 (1989) 533

Pa60,63 A. Pais, Annals of Phys. 9(1960) 548; 22 (1963) 274; see also S.J. Orfanidis and V. Rittenberg, Nucl. Phys. B59 (1973) 570

Pa78 P. Pavlopoulos et al., Phys. Lett. 72B (1978) 415

Pl93 H. S. Plendl, Physica Scripta 48 (1993) 160

Po95 D. Polster et al., Phys. Rev. C51 (1995) 1167

RMP98 C. Amsler , Rev. Mod. Phys. 591 (1998) 1293 and ref. therein

Va88 J. Vandermeulen, Z. Phys. C 37 (1988) 563

Zi88 M. Ziegler et. al., Phys. Lett. B 206 (1988) 151

Ancillary material

Distribution between neutral and charged pions at rest in LH_2

(%)

add $K, \eta, \omega \rightarrow \pi^0\gamma...$

	$0\pi^0$	$1\pi^0$	$2\pi^0$	$3\pi^0$	$4\pi^0$	$5\pi^0$	Total = 84.5
2π	0.33 ± 0.01		0.17 ± 0.01 †$(6.9 \pm 0.4) \times 10^{-2}$				0.50
3π		6.9 ± 0.4		1.2 ± 0.1 †0.62 ± 0.10			8.1 ± 0.5
4π	6.9 ± 0.6		13.8 ± 1.2 †9.3 ± 0.2		1.1 ± 0.1 †0.31 ± 0.02		20.9 ± 1.8
5π		19.6 ± 0.7		13.1 ± 0.5 †9.7 ± 0.6		0.65 ± 0.02 †0.71 ± 0.14	33.3 ± 1.2
6π	2.1 ± 0.2		9.5 ± 0.9		3.1 ± 0.3		14.7 ± 1.4
7π		1.9 ± 0.2		4.5 ± 0.5		0.57 ± 0.06	7.0 ± 0.7

Measured in BBC

Factorial law

Data from Crystal Barrel

Poor agreement for low multiplicities (resonances, selection rules from quantum number conservation)

2-body in liquid H_2

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TABLE II. Branching ratios B for $\bar{p}p$ annihilation at rest in liquid. See Amsler and Myhrer (1991) for annihilation in gaseous hydrogen. Further branching ratios from Dalitz plot analyses are listed in Table XIII below.

Channel		B			Reference
e^+e^-	3.2	±	0.9	10^{-7}	Bassompierre *et al.* (1976)
$\pi^0\pi^0$	6.93	±	0.43	10^{-4}	Amsler *et al.* (1992a)‡
	4.8	±	1.0	10^{-4}	Devons *et al.* (1971)
$\pi^+\pi^-$	3.33	±	0.17	10^{-3}	Armenteros and French (1969)
$\pi^+\pi^-$	3.07	±	0.13	10^{-3}	Amsler *et al.* (1993b)‡
$\pi^0\eta$	2.12	±	0.12	10^{-4}	Amsler *et al.* (1993b)‡
$\pi^0\eta'$	1.23	±	0.13	10^{-4}	Amsler *et al.* (1993b)‡
$\pi^0\rho^0$	1.72	±	0.27	10^{-2}	Armenteros and French (1969)
$\pi^\pm\rho^\mp$	3.44	±	0.54	10^{-2}	Armenteros and French (1969)
$\eta\eta$	1.64	±	0.10	10^{-4}	Amsler *et al.* (1993b)‡
$\eta\eta'$	2.16	±	0.25	10^{-4}	Amsler *et al.* (1993b)‡
$\omega\pi^0$	5.73	±	0.47	10^{-3}	Amsler *et al.* (1993b) [a]‡
	6.16	±	0.44	10^{-3}	Schmid (1991) [b]‡
$\omega\eta$	1.51	±	0.12	10^{-2}	Amsler *et al.* (1993b) [a]‡
	1.63	±	0.12	10^{-2}	Schmid (1991) [b]‡
$\omega\eta'$	0.78	±	0.08	10^{-2}	Amsler *et al.* (1993b)‡
$\omega\omega$	3.32	±	0.34	10^{-2}	Amsler *et al.* (1993b)‡
$\eta\rho^0$	4.81	±	0.85	10^{-3}	[c]
	3.87	±	0.29	10^{-3}	Abele *et al.* (1997a)‡
$\eta'\rho^0$	1.29	±	0.81	10^{-3}	Foster *et al.* (1968a)
	1.46	±	0.42	10^{-3}	Urner (1995)‡
$\rho^0\rho^0$	1.2	±	1.2	10^{-3}	Armenteros and French (1969)
$\rho^0\omega$	2.26	±	0.23	10^{-2}	Bizzarri *et al.* (1969)
K^+K^-	1.01	±	0.05	10^{-3}	Armenteros and French (1969)
K^+K^-	0.99	±	0.05	10^{-3}	Amsler *et al.* (1993b)‡
K_SK_L	7.6	±	0.4	10^{-4}	Armenteros and French (1969)
K_SK_L	9.0	±	0.6	10^{-4}	Amsler *et al.* (1995c)‡

[a] From $\omega\rightarrow\pi^0\gamma$.
[b] From $\omega\rightarrow\pi^+\pi^-\pi^0$.
[c] Average between Baltay *et al.* (1966), Espigat *et al.* (1972) and Foster *et al.* (1968a).
‡Crystal Barrel experiment.

TABLE III. Pseudoscalar mixing angle θ_p derived from the measured ratios of two-body branching ratios ($\theta_i = 35.3°$). The first four rows assume only the quark line rule in the annihilation process. The last six rows assume in addition the dominance of the annihilation graph A.

Ratio	Prediction	θ_p (deg)
$\tilde{B}(\pi^0\eta)/\tilde{B}(\pi^0\eta')$	$\tan^2(\theta_i - \theta_p)$	-18.1 ± 1.6
$\tilde{B}(\eta\eta)/\tilde{B}(\eta\eta')$	$\frac{1}{2}\tan^2(\theta_i - \theta_p)$	-17.7 ± 1.9
$\tilde{B}(\omega\eta)/\tilde{B}(\omega\eta')$	$\tan^2(\theta_i - \theta_p)$	-21.1 ± 1.5
$\tilde{B}(\eta\rho^0)/\tilde{B}(\eta'\rho^0)$	$\tan^2(\theta_i - \theta_p)$	$-25.4 \pm^{5.0}_{2.9}$
$\tilde{B}(\eta\rho^0)/\tilde{B}(\omega\pi^0)$	$\sin^2(\theta_i - \theta_p)$	-11.9 ± 3.2
$\tilde{B}(\eta'\rho^0)/\tilde{B}(\omega\pi^0)$	$\cos^2(\theta_i - \theta_p)$	-30.5 ± 3.5
$\tilde{B}(\eta\eta)/\tilde{B}(\pi^0\pi^0)$	$\sin^4(\theta_i - \theta_p)$	$-6.2 \pm^{0.6}_{1.1}$
$\tilde{B}(\eta\eta')/\tilde{B}(\pi^0\pi^0)$	$2\sin^2(\theta_i - \theta_p) \times \cos^2(\theta_i - \theta_p)$	14.6 ± 1.8 or -34.0 ± 1.8
$\tilde{B}(\omega\eta)/\tilde{B}(\pi^0\rho^0)$	$\sin^2(\theta_i - \theta_p)$	$-23.7 \pm^{7.6}_{8.9}$
$\tilde{B}(\omega\eta')/\tilde{B}(\pi^0\rho^0)$	$\cos^2(\theta_i - \theta_p)$	-20.1 ± 3.7

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OZI tests

TABLE VI. Branching ratios for ϕ production at rest in liquid.

Channel	B				Reference
$\pi^0\phi$	6.5	$\pm$	0.6	10^{-4}	[a]‡
$\pi^0\phi$	3.0	$\pm$	1.5	10^{-4}	Chiba *et al.* (1988)
$\pi^0\phi$	4.0	$\pm$	0.8	10^{-4}	Reifenröther *et al.* (1991) [b, c]
$\eta\phi$	7.8	$\pm$	2.1	10^{-5}	Amsler *et al.* (1995c)‡
$\eta\phi$	3.0	$\pm$	3.9	10^{-5}	Reifenröther *et al.* (1991) [b]
$\eta\phi$	7.6	$\pm$	3.1	10^{-5}	Albernico *et al.* (1998)
$\omega\phi$	6.3	$\pm$	2.3	10^{-4}	Bizzarri *et al.* (1971)
$\omega\phi$	5.3	$\pm$	2.2	10^{-4}	Reifenröther *et al.* (1991) [b, d]
$\rho^0\phi$	3.4	$\pm$	1.0	10^{-4}	Reifenröther *et al.* (1991) [b]
$\gamma\phi$	2.0	$\pm$	0.4	10^{-5}	[a]‡

[a]Updates Amsler *et al.* (1995c).
[b]Annihilation in gas extrapolated to pure S-wave annihilation.
[c]Using Chiba *et al.* (1988) in liquid.
[d]Using Bizzarri *et al.* (1971) in liquid.
‡Crystal Barrel experiment.

TABLE VII. Ratio of ϕ to ω production in low-energy annihilation in liquid.

X	$\tilde{R}_X[10^{-2}]$		
γ	29.4	$\pm$	9.7
π^0	10.6	$\pm$	1.2
η	0.46	$\pm$	0.13
ω	1.02	$\pm$	0.39
ρ^0	1.57	$\pm$	0.49
π^-	13.0	$\pm$	2.5
π^+	10.8	$\pm$	1.5
σ	1.75	$\pm$	0.25
$\pi^+\pi^-$	1.65	$\pm$	0.35

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Pontecorvo branching ratios

$\bar{p}d \to \pi^- p$	$(1.41 \pm 0.14) \times 10^{-5}$
$\bar{p}d \to \pi^0 n$	$(7.02 \pm 0.72) \times 10^{-6}$
$\bar{p}d \to \eta n$	$(3.19 \pm 0.48) \times 10^{-6}$
$\bar{p}d \to \omega n$	$(22.8 \pm 4.1) \times 10^{-6}$
$\bar{p}d \to \eta' n$	$(8.2 \pm 3.4) \times 10^{-6}$
$\bar{p}d \to \phi n$	$(3.56 \pm 0.25 \times 10^{-6}$
$\bar{p}d \to \Sigma^0 K^0$	$(2.35 \pm 0.45) \times 10^{-6}$
$\bar{p}d \to \Lambda K^0$	$(2.15 \pm 0.45) \times 10^{-6}$

Radiative annihilation

TABLE V. Branching ratios B for radiative $\bar{p}p$ annihilation at rest in liquid from Crystal Barrel (Amsler *et al.,* 1993c, 1995c). The lower and upper limits L and U, calculated from the vector dominance model, are given in the third and fourth column, respectively.

Channel	B				L	U
$\pi^0\gamma$	4.4	±	0.4	$\times 10^{-5}$	3.1×10^{-5}	6.8×10^{-5}
$\eta\gamma$	9.3	±	1.4	$\times 10^{-6}$	1.0×10^{-6}	2.5×10^{-5}
$\omega\gamma$	6.8	±	1.8	$\times 10^{-5}$	8.5×10^{-6}	1.1×10^{-4}
$\eta'\gamma$	<1.2			$\times 10^{-5}$ [a]	2.7×10^{-7}	10^{-5}
$\gamma\gamma$	<6.3			$\times 10^{-7}$ [a]		
$\phi\gamma$	2.0	±	0.4	$\times 10^{-5}$	2.1×10^{-7}	1.5×10^{-6}

[a]Upper limit (95% confidence).

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3-body in liquid H_2

TABLE IX. Branching ratios for $\bar{p}p$ annihilation at rest into three narrow mesons. Mesons in parentheses were not detected.

Channel	Final state	B				Reference
$\pi^0\pi^0\pi^0$	6γ	6.2	±	1.0	10^{-3}	Amsler *et al.* (1995f)‡
$\pi^+\pi^-\pi^0$	$\pi^+\pi^-(\pi^0)$	6.9	±	0.4	10^{-2}	Foster *et al.* (1968b)
$\pi^0\eta\eta$	6γ	2.0	±	0.4	10^{-3}	Amsler *et al.* (1995e)‡
$\pi^0\pi^0\omega$	7γ	2.00	±	0.21	10^{-2}	Amsler *et al.* (1993a)‡
	$\pi^+\pi^-6\gamma$	2.57	±	0.17	10^{-2}	Amsler *et al.* (1994d)‡
$\pi^+\pi^-\omega$	$2\pi^+2\pi^-(\pi^0)$	6.6	±	0.6	10^{-2}	Bizzarri *et al.* (1969)
$\omega\eta\pi^0$	7γ	6.8	±	0.5	10^{-3}	Amsler *et al.* (1994c)‡
$\pi^0\pi^0\eta$	6γ	6.7	±	1.2	10^{-3}	Amsler *et al.* (1994b)‡
	$\pi^+\pi^-6\gamma$	6.50	±	0.72	10^{-3}	Amsler *et al.* (1994d)‡
$\pi^+\pi^-\eta$	$\pi^+\pi^-2\gamma$	1.63	±	0.12	10^{-2}	Abele *et al.* (1997a)‡
	$\pi^+\pi^-6\gamma$	1.33	±	0.16	10^{-2}	Amsler *et al.* (1994d)‡
	$2\pi^+2\pi^-(\pi^0)$	1.38	±	0.17	10^{-2}	Espigat *et al.* (1972)
	$2\pi^+2\pi^-(\pi^0)$	1.51	±	0.17 0.21	10^{-2}	Foster *et al.* (1968a)
$\pi^0\pi^0\eta'$	10γ	3.2	±	0.5	10^{-3}	Abele *et al.* (1997e)‡
	6γ	3.7	±	0.8	10^{-3}	Abele *et al.* (1997e)‡
$\pi^+\pi^-\eta'$	$\pi^+\pi^-6\gamma$	7.5	±	2.0	10^{-3}	Urner (1995)‡
	$3\pi^+3\pi^-(\pi^0)$	2.8	±	0.9	10^{-3}	Foster *et al.* (1968a)
$\pi^0\eta\eta'$	6γ	2.3	±	0.5	10^{-4}	Amsler *et al.* (1994f)‡
$\pi^0\pi^0\phi$	$8\gamma(K_L)$	9.7	±	2.6	10^{-5}	Abele *et al.* (1997c)‡
$\pi^+\pi^-\phi$	$2\pi^+2\pi^-(K_L)$	4.6	±	0.9	10^{-4}	Bizzarri *et al.* (1969)
$\pi^0K_SK_L$	$3\pi^0(K_L)$	6.7	±	0.7	10^{-4}	Amsler *et al.* (1993d) [a]‡
$\pi^0K_SK_S$	$2\pi^+2\pi^-(\pi^0)$	7.5	±	0.3	10^{-4}	[b]
$\pi^\pm K^\mp K_S$	$\pi^+\pi^-\pi^\pm K^\mp$	2.73	±	0.10	10^{-3}	[b]
$\pi^\pm K^\mp K_L$	$\pi^\pm K^\mp(K_L)$	2.91	±	0.34	10^{-3}	Abele *et al.* (1998d)‡
ωK_SK_S	$3\pi^+3\pi^-(\pi^0)$	1.17	±	0.07	10^{-3}	Bizzarri *et al.* (1971)
ωK^+K^-	$K^+K^-\pi^+\pi^-(\pi^0)$	2.30	±	0.13	10^{-3}	Bizzarri *et al.* (1971)

[a]Using $B(\pi^0\phi)$ from Table VI and Eq. (47).
[b]Average between Armenteros *et al.* (1965) and Barash *et al.* (1965).
‡Crystal Barrel experiment.

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Kaonic channels in liquid H_2

TABLE XI. Branching ratios for $\bar{p}p$ annihilation at rest in liquid into kaonic channels. The branching ratios include only the decay mode of the intermediate resonance leading to the observed final state.

Channel / Subchannel	$\bar{p}p(I)$	Contributing resonances / Branching ratio
$\pi^0 K_L K_L$		$K^*(892), K_0^*(1430), a_2(1320), f_2(1270), f_2'(1525)$ $f_0(1370), f_0(1500), a_0(1450)$
Total [a]		$(7.5\pm0.3)\times10^{-4}$
$K^*(892)\bar{K}$	$^1S_0(0,1)$	$(8.71\pm0.68)\times10^{-5}$
$K_0^*(1430)\bar{K}$		$(4.59\pm0.46)\times10^{-5}$ [b]
$a_2(1320)\pi^0$	$^1S_0(0)$	$(6.35\pm0.74)\times10^{-5}$
$a_0(1450)\pi^0$		$(7.35\pm1.42)\times10^{-5}$ [c]
$f_2(1270)\pi^0$	$^1S_0(1)$	$(4.25\pm0.59)\times10^{-5}$
$f_2'(1525)\pi^0$		$(1.67\pm0.26)\times10^{-5}$
$f_0(1370)\pi^0$		$(2.20\pm0.33)\times10^{-4}$
$f_0(1500)\pi^0$		$(1.13\pm0.09)\times10^{-4}$
$\pi^\pm K^\mp K_L$		$K^*(892), K_0^*(1430), a_2(1320)$ $a_0(980), a_0(1450), \rho(1450/1700)$
Total [a]		$(2.73\pm0.10)\times10^{-3}$
$K^*(892)\bar{K}$	$^1S_0(0)$	$(2.05\pm0.28)\times10^{-4}$
$K_0^*(1430)\bar{K}$		$(8.27\pm1.93)\times10^{-4}$ [b]
$a_0(980)\pi$		$(1.97^{+0.15}_{-0.34})\times10^{-4}$
$a_2(1320)\pi$		$(3.99^{+0.31}_{-0.83})\times10^{-4}$
$a_0(1450)\pi$		$(2.95\pm0.56)\times10^{-4}$
$K^*(892)\bar{K}$	$^1S_0(1)$	$(3.00\pm1.10)\times10^{-5}$
$K_0^*(1430)\bar{K}$		$(1.28\pm0.55)\times10^{-4}$ [b]
$\rho(1450/1700)\pi$		$(8.73^{+1.40}_{-2.75})\times10^{-5}$
$K^*(892)\bar{K}$	$^3S_1(0)$	$(1.50\pm0.41)\times10^{-4}$
$\rho(1450/1700)\pi$		$(8.73\pm2.75)\times10^{-5}$
$K^*(892)\bar{K}$	$^3S_1(1)$	$(5.52\pm0.84)\times10^{-4}$
$a_2(1320)\pi$		$(1.42\pm0.44)\times10^{-4}$

[a]From the corresponding K_S channels (Armenteros *et al.*, 1965; Barash *et al.*, 1965).
[b]Includes low-energy $K\pi$ scattering.
[c]Fixed by $\pi^\pm K^\mp K_L$ data.

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If R dominates

no $(d\bar{d})(d\bar{d})$

$$|a^2\sqrt{2BR(\pi^0\pi^0)} - \sqrt{2BR(\eta\eta)}|^2 \leq 4a^2BR(\pi^0\eta) \leq |a^2\sqrt{2BR(\pi^0\pi^0)} + \sqrt{2BR(\eta\eta)}|^2$$

with $a = \sin(\theta_i - \theta_P)$ Data: $6.9 \times 10^{-7} < 5.4 \times 10^{-6} < 1.7 \times 10^{-5}$

Genz, H., M. Martinis, and S. Tatur, 1990, Z. Phys. A **335**, 87.